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Apodibius serventyi sp.nov., a new clawless water-bear [Invertebrata: Tardigrada] from Western Australia

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Abstract

Apodibius serventyi sp.nov.is described on the basis of examination of 34 specimens obtained from three localities around Perth, Western Australia. A morphometric analysis of the specimens is complemented by light microscope and scanning electron microscope images. The systematic position of *Apodibius serventyi* sp.nov. within the Tardigrada is considered.

Introduction

The Tardigrada are small, multicellular animals between 50μm and 1200μm long, though rarely exceed 500μm. They occupy the surface water films of mosses, liverworts, lichens, and some algae or the water-filled spaces in soil, marine and freshwater sand and sediments (Morgan and King 1976). In woodland litter they may inhabit the interstices of decomposing leaves, particularly willow, and some species exploit a range of herbivore dung (Morgan 1982). Utilizing this specialised range of habitats tardigrades can attain densities up to several millions per square metre in marine sand or on a moss encrusted roof (Morgan 1977). The group has a world-wide distribution (Ramazzotti and Maucci 1983).

There is an extensive literature on tardigrades dominated by studies from North America and European localities. Australia has been overlooked except for contributions by Richters (1908) who observed the ubiquitous *Macrobiotus hufelandi* (Schultze) at Katoomba in the Blue Mountains and Murray (1910) who recorded 31 species, several new to science, from New South Wales and Queensland. Murray noted that the Australian fauna was very localised and showed many peculiarities. There is every indication that recent research initiatives will confirm this contention.

In the course of studies on the Tardigrada of Western Australia the authors found 34 specimens of a clawless water-bear belonging to the recently described genus *Apodibius* Dastych, 1983. The specimens differed in several respects from the type species *Apodibius confusus* Dastych, the sole representative of the genus described to date. *A. confusus* had been described on the basis of three specimens extracted from mosses overlying soil in NW Poland (Dastych, 1983). The genus *Apodibius* differs distinctly from all known genera of Tardigrada in lacking any claw-like structures on all four pairs of legs.

Apodibius serventyi sp.nov.

Diagnosis: An *Apodibius* with three macroplacoids in the pharyngeal bulb.

Description of holotype: Length 355μm. The body is hyaline and lacks pigmentation. Cuticle smooth and featureless. Eye spots present, positioned at about the level of the stylet supports (Fig. 1A). Mouth terminal and surrounded by six low, hemispherical peribuccal lobes. Buccal apparatus of the *Macrobiotus* type with a well-developed strengthening bar (Fig. 1B). Buccal tube smooth and slightly curved downwards over the anterior third of it length. Buccal tube of uniform width (4μm) over most of its length, widening at the bulb where the wall is also thicker. Pharyngeal bulb pear-shaped, 33μm long x 28μm broad, with the greatest width in the posterior third. Bulb with almost triangular apophysis 2.5μm long overlying the end of the tube. Three macroplacoids, each a rod with well-rounded ends, 3, 3.5 and 4μm long respectively. Macroplacoids close together, the first and second connected by a narrow neck which can be observed only under oil immersion by altering the plane of focus. Pharyngeal rods occupy the anterior two-thirds of the bulb. Microplacoid absent. Legs small and variably developed, 17, 35, 26, and 18μm in length from first to fourth pairs (Fig. 1A). Each leg with a smooth outline except for low protuberances: one, 5μm high, on each of the first pair of legs; three, 3, 7 and 3μm high, on the second pair of legs; two, 6μm high, on the third pair of legs; and two, 5 and 7μm high on the fourth pair of legs. No claws or other sclerified structures (Figs 1C, D, E, F).

Description of paratypes: Length 188μm to 430μm. Body hyaline, lacking pigmentation. Eyespots generally absent; only observed in four out of 33 specimens. Mouth terminal or slightly sub-terminal and surrounded by six peribuccal lobes (Figs 2A, 3A, C). Anterior edge of mouth of some specimens circled by a narrow wreath of small elliptical thickenings which are only discerned with great difficulty. Buccal apparatus of the *Macrobiotus* type with well-developed strengthening bar. Stylets bellied out in the middle and arrangement of furca asymmetrical. Buccal tube smooth and often curved ventrally at the anterior end. Length of tube 8 to 13% of total body length. Dimensions of bulb variable, often a short pear shape with the greatest width across the posterior third, sometimes spherical or almost so, occasionally shorter than broad. Triangular apophysis and three macroplacoids, the latter rods with rounded ends. Macroplacoids of equal length, increasing in length from one to three, or the first or second may be longest. The first and second macroplacoids connected by a narrow neck. Microplacoid always absent.

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First and fourth pairs of legs poorly developed, second and third pairs less so. Claws or other sclerified structures completely absent. Each leg usually with at least one low terminal protuberance, often two, sometimes three (Fig. 2B, 3B, 4).

The locomotion of one live specimen was noted prior to permanent slide preparation. The animal moved easily if sinuously through flocculent matter settled at the bottom of a petri dish. *Apodibius serventyi* sp.nov. traversed this material faster than clawed species also present in the sample; the latter reached for and held on to material in their progression and were slower in consequence. No eggs were found, although several specimens displayed a ventral genital pore (Fig. 3D).

Type locality: Moss from the vertical face of a limestone retaining wall by the walk-through aviary at South Perth Zoo (holotype and 26 paratypes). Moss growing in the cracks between paving slabs from a back garden at Woodlands, a northern suburb of Perth (two paratypes). Moss growing on soil from an island garden in an ornamental pool at the Cottesloe Civic Centre, a coastal suburb west of Perth (five paratypes, including a simplex individual).

Type repository: Western Australian Museum, Francis Street, Perth 6000, Western Australia.

Registration numbers are as follows:

WAM 86/356 Holotype on a SEM stub

WAM 86/349-53 Five paratypes on a microscope slide

WAM 86/354-5 Two paratypes on a SEM stub

We are pleased to name this species after the Australian naturalist Dr Dominic L. Serventy.

Table 1

Apodibius serventyi sp. nov.—measurements of type specimens.

Measurements (in μm)	Holotype	Paratype Mean	SD
Body length	355	360	±66
Tube length	32	35	± 4.7
Tube external diameter	4	4.5	± 0.7
Bulb length	33	36.8	± 5.5
Bulb width	28	35.7	± 6.2
Apophysis length	2.5	2.8	± 0.5
First macroplacoid length	3	4.2	± 1.3
Second macroplacoid length	3.5	4.2	± 0.7
Third macroplacoid length	4	4.7	± 1.0

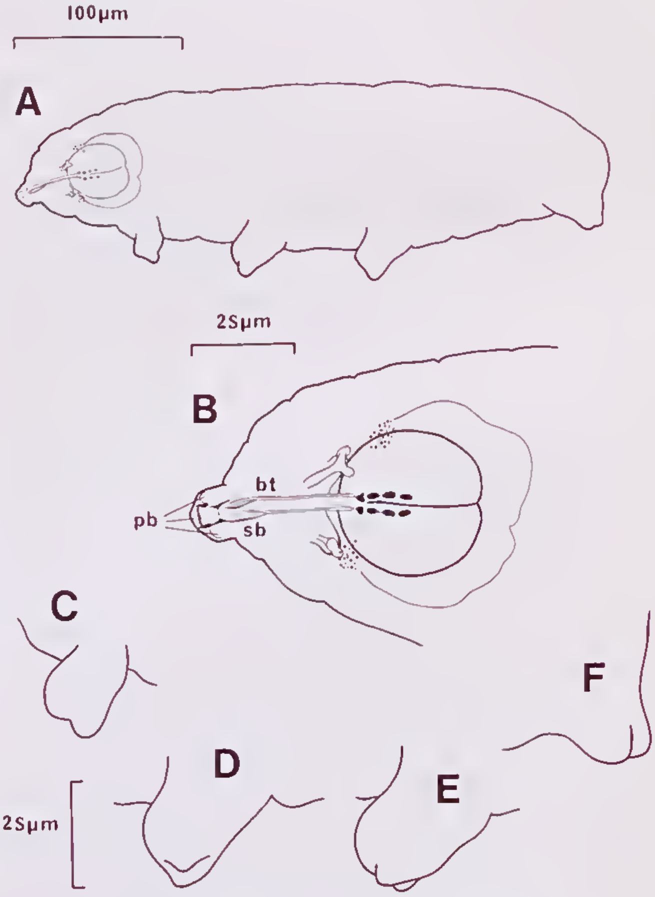

Figure 1.—*Apodibius serventyi* sp. nov. Holotype

A. Entire
B. Pharyngeal apparatus
bt buccal tube
pb peribuccal lobes
sb strengthening bar
C, D, E, F. Legs 1 to 4 respectively.

Discussion

Dastych (1983) described the systematic position within the Eutardigrada of *Apodibius confusus* as unclear "because of the strong reduction of legs and above all, the complete lack of claws". The description of *Apodibius serventyi* sp. nov. while confirming the unique character of the genus has done little to extend our knowledge of systematic affinity.

Currently, there are two schools of thought on the importance of characters which are used to determine systematic arrangement within the Eutardigrada. Pilato (1969 a,b) proposed a classification in which claw structure predominated over bucco-pharyngeal apparatus. This system has gained widespread acceptance among tardigradologists. Recently, Schuster *et al.* (1980) devised a revision of the Eutardigrada in which the arrangement of the bucco-pharyngeal apparatus, and in particular the possession of a buccal tube support, is given increased prominence and new familial arrangements devised accordingly. This new arrangement has generated criticism, notably that of Bertolani (1981), who considers the subdivision into families proposed by Pilato (1969 a,b) more acceptable phylogenetically, and Pilato (1982) who, we believe, successfully re-appraises the justification for his original taxonomy with the addition of information on recently described genera and species.

Pilato (1982) advances the hypothesis that if a structure has given rise to relatively few morphological variants, as is the case with claw structure in the Eutardigrada, then it can be judged to be very stable. Taxa recognised on the basis of differences in this structure can, therefore, be identified as evolutionary lines which have been diverging for a considerable period of time. In contrast to this situation of morphological stability allied to systematic importance, more complex structures such as the bucco-pharyngeal apparatus may not have the same phylogenetic significance; because they are complex there is a greater chance of them developing myriad minor variations in response to natural selection pressures.

Figure 2.—A. *Apodibius serventyi* sp. nov. Paratype. Entire. Note position of mouth (arrow). Scale line 100 μm. Phase contrast illumination.

B. *Apodibius serventyi* sp. nov. Paratype. Anterior end. Note protuberances on first and second legs (arrows). Scale line 50 μm. Nomarski illumination.

The new species *Apodibius serventyi* has been separated from the only other known representative of the genus *Apodibius* on the basis of a minor modification in the bucco-pharyngeal apparatus. Such differences are used frequently to determine species within the Eutardigrada. However, the affinities of a clawless genus in an order in which the accepted familial sub-divisions, according to Pilato (1982), are on the basis of claw structure are not readily identifiable.

In the systematic arrangement of the Eutardigrada devised by Pilato (1969 a, b, revised 1982) the order comprises four families, Macrobiotidae, Calohypsibiidae, Hypsibiidae, and Milnesiidae, plus the monotypic genus *Necopinatum* (Pilato, 1971) accorded the status incertae sedis. Within these families the claw type is characteristic and constant for each but the pattern of the bucco-pharyngeal apparatus can vary. The clawless *Apodibius* with *Macrobiotus* type bucco-pharyngeal apparatus shares possession of the latter character with genera in three families: *Doryphoribius* in the Hypsibiidae; *Haplomacrobiotus, Hexapodibius* and *Parahexapodibius* in the Calohypsibiidae; *Macrobiotus, Minibiotus*, and *Dactylobiotus* in the *Macrobiotidae*. Only within the Calohypsibiidae is there a tendency towards reduction of legs and claws comparable to that described for *Apodibius*. The authors support the view of Dastych (1983) that the genus *Apodibius* represents a stage of an evolutionary line along which leg and claw structure are being reduced. It is probable that with the increasing attention being paid to Tardigrada the discovery of new forms will help resolve debate about the status of *Apodibius*.

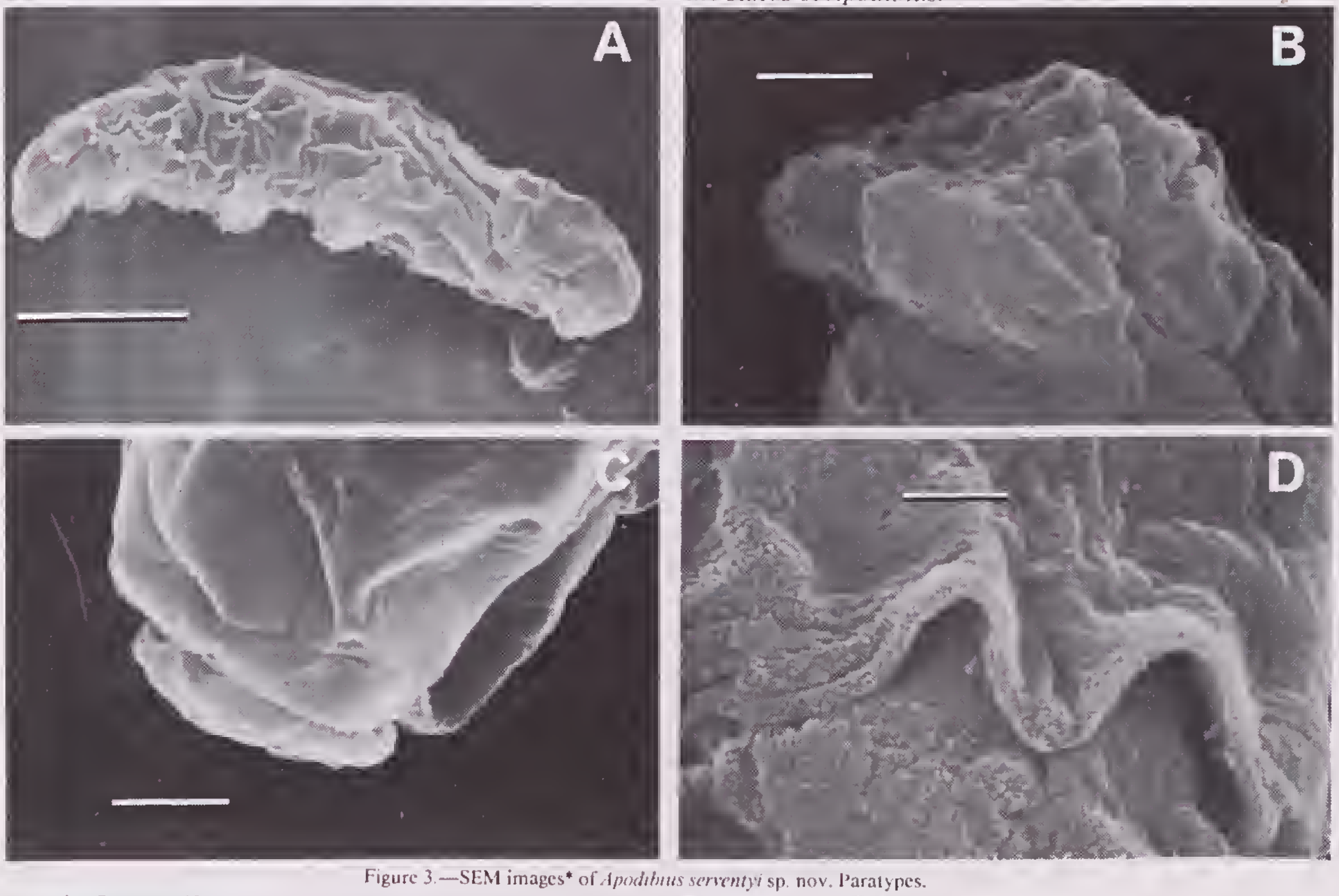

Figure 3.—SEM images* of *Apodibius serventyi* sp. nov. Paratypes.

A. Entire. Scale line 50 μm
B. Fourth legs. Scale line 10 μm
C. Mouth with peribuccal lamellae. Scale line 5 μm
D. Ventral genital pore. Scale line 2.5 μm

* Note: All SEM images produced on a JEOL 1200 EX with ASID at 80Kv. Material critical point dried and gold sputter coated.

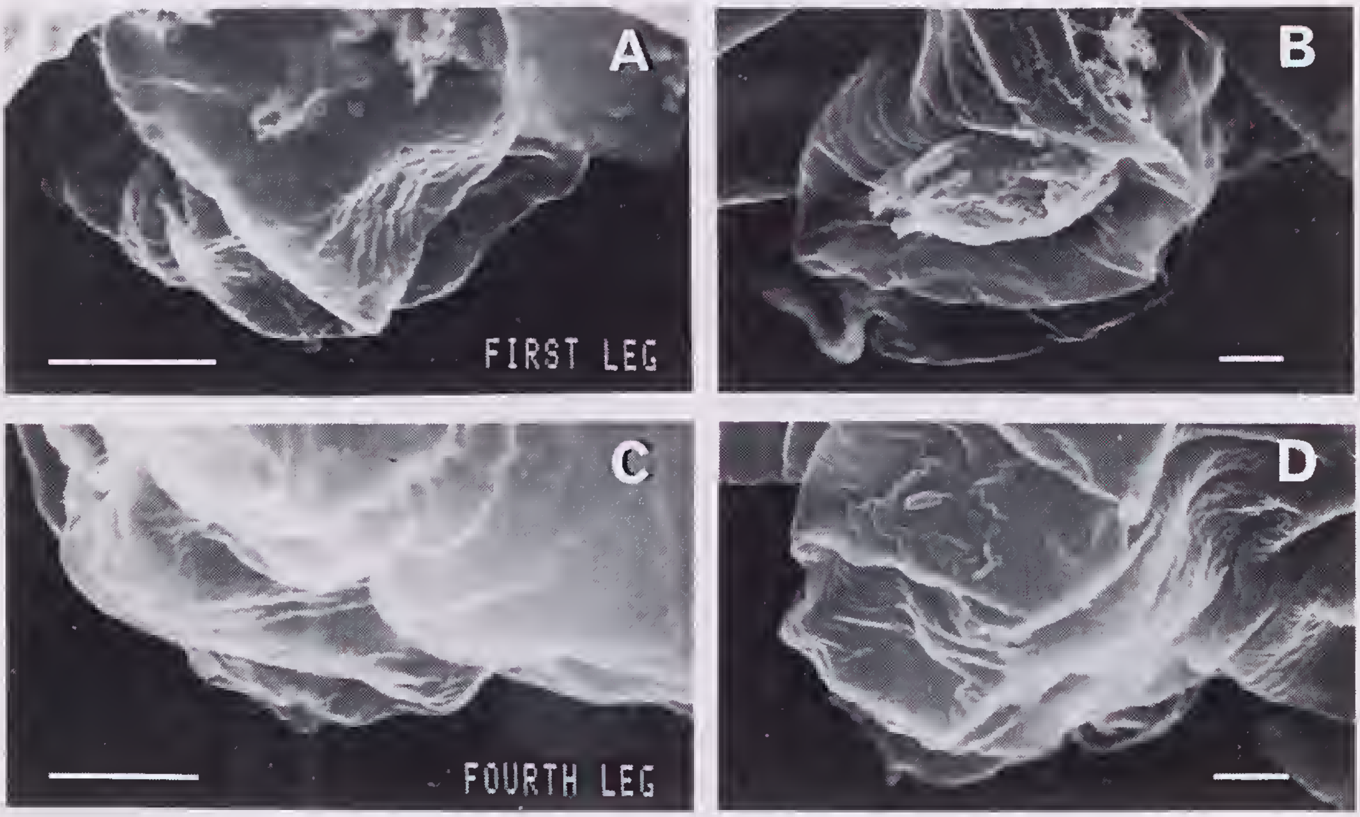

Figure 4.—SEM images of legs of *Apodibius serventyi* sp. nov. Paratype.
A. First leg B. Second leg C. Fourth leg D. Third leg
Scale line 2.5μm

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Australites from the Kimberley region, Western Australia

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Abstract

The australite strewnfield, thought to be restricted to the region south of latitudes 24-25°S, has been shown by recent collections to extend to the Kimberley region of Western Australia. These collections include both normal and HMg (high-magnesium) australites.

Introduction

Chalmers *et al.* (1976), on the basis of their own field collecting and on published reports, proposed that the australite strewnfield was essentially restricted to the region south of latitudes 24° to 25°S. The few australites found north of this region were ascribed to specimens transported by man. However, since that publication intensive prospecting in the Kimberley region has resulted in the incidental recovery of australites in situations which appear to preclude human transport, and hence require a re-evaluation of the extent of the Australian strewnfield.

The King George River australites

A small collection of nine specimens from the King George River area was studied. These were collected in stream gravels and show typical abraded subspherical and lensoid forms. Weight information is provided in Table 1, along with specific gravity (S.G.), refractive index (R. I.), and microprobe analyses. The microprobe analyses were made at the Smithsonian Institution, with a synthetic glass of approximate tektite composition as a standard (Mason 1979, p. 15-16).

The analyses all fall within the range of australite compositions established by Taylor (1962), Taylor and Sachs (1964), Chapman and Scheiber (1969), Chapman (1971), and Mason (1979). In terms of the Chapman (1971) classification of tektites, most of these specimens fall in his "normal" group (CaO > MgO, Na_2O >1.25%), which includes practically all the analysed australites from Western Australia and the extension of the Nullarbor Plain into South Australia. DY3, MF2, and MF4 are included in the normal group, although their Na_2O contents are less than 1.25%. Two specimens, DRY2 and DRY3, belong to Chapman's HMg (high-magnesium) group, otherwise concentrated in the Lake Wilson—Mount Davies area near the Western Australia—Northern Territory—South Australia border region.

Previous records of australites from the Kimberley region

Cleverly and Dortch (1975) recorded the recovery of six australites from archaeological sites in the Ord Valley, within the area now largely inundated by Lake Argyle. They considered the possibility that they were the result of a natural fall in that region, but thought it more likely that they were the result of long-range trade from southern regions.

Horwitz and Hudson (1977) analysed and described 12 tektites from northern Western Australia. Nine of these were from the Pilbara region and three from the Kimberley region (near 16°S, 129°E). Of these three, one is a normal australite, one a HMg australite, and the third they considered to be an indochinite, on the basis of low MgO and CaO contents of 1.27% and 1.50% respectively. However australites with similar low MgO and CaO contents are known (e.g. Mason, 1979, Table 1,

Table 1.
Analyses of King George River australites

	DF3	DY3	DR3	DRY2	DR2	DY2	DRY3	MF4	MF2
SiO_2	71.5	71.9	72.0	72.2	73.5	74.2	74.7	75.6	77.3
Al_2O_3	13.3	13.1	13.0	13.0	12.4	12.6	11.9	11.9	10.8
FeO	4.61	4.79	4.95	5.35	4.41	4.67	4.30	4.31	3.72
MgO	2.31	2.59	2.60	3.41	2.27	2.49	3.22	2.17	1.78
CaO	3.36	3.49	3.04	3.16	3.35	3.19	1.82	1.87	2.47
K_2O	2.38	2.33	2.37	1.90	2.28	2.28	1.71	1.96	2.11
Na_2O	1.37	1.22	1.40	1.10	1.30	1.34	0.81	0.85	1.16
TiO_2	0.72	0.69	0.72	0.69	0.67	0.69	0.58	0.64	0.58
Sum	99.6	100.1	100.1	100.8	100.2	101.5	99.0	99.3	99.8
S.G.	2.453	2.463	2.462	2.463	2.435	2.443	2.435	2.416	2.400
R.I.	1.507	1.513	1.512	1.513	1.505	1.508	1.505	1.503	1.501
Weight (g)	0.364	1.322	12.577	7.268	11.468	4.725	4.128	0.097	0.287

Locations: DR – King George River, 14 26'S, 127 20'E; DRY, DY = Beta Creek, 14 18'S, 127 16'E; MF = Morellis Fox, 14 18'S, 127 20'E

analyses 26, 38, 45), so the identification of their analysed specimen as an indochinite is intriguing but not compelling.

Horwitz and Hudson pointed out the significance of their identification of HMg tektites in the Pilbara and Kimberley regions, thereby extending the geographic extent of this specific group from the previously limited area around the Western Australia—Northern Territory—South Australia border. My data confirm this. However, it is puzzling that no HMg australites were found in large collections from Earaheedy and Granite Peak, midway between Mount Davies and the Pilbara (Mason, 1979). I have also searched for australites and made extensive inquiries in the desert area between Mount Davies and the Kimberley, I found none, and the natives around Balgo Hills (20°07'S, 127°48'E) said that none were known in that region. These and similar gaps in australite distribution suggest an erratic and discontinuous pattern of shower or showers.

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Salmonella infections and animal condition in the mainland and Bald Island populations of the quokka (*Setonix brachyurus:* Marsupialia)

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Abstract

The cause and significance of *Salmonella* infections in the quokka have been studied previously on Rottnest Island (Western Australia) where the animals live in a disturbed habitat under seasonally adverse conditions. In the study reported here *Salmonella* infections and animal condition were examined in mainland and an isolated island population where the animals were believed to be living under more favourable conditions. On the mainland, where the animals do not suffer seasonally adverse conditions, *Salmonella* infections were uncommon. Under the stress of caging, however, the animals became markedly susceptible to infection. On Bald Island, which is remote and little disturbed by human activities, the animals were found to be suffering a summer starvation similar to but not as severe as that seen on Rottnest island. *Salmonella* infections were correspondingly common, with 32% of the animals positive, and included some serotypes typically associated with urban and agricultural ecosystems. Morphometric differences were found between all populations. The results are discussed in terms of the biology of the quokka, and suggest that the Rottnest Island quokka suffered annual starvation before historical records.

Introduction

The cause and significance of *Salmonella* infections in the quokka on Rottnest Island (Western Australia, Fig. 1) have been described by Hart, Bradshaw and Iveson (1985) and Hart, Iveson and Bradshaw (in prep.) These authors found that the Rottnest quokka suffers a dramatic summer proliferation of *Salmonella* infections as a result of the poor quality of forage available to the animals during the hot and dry summer. Although the animals declined seriously in condition during the summer the *Salmonella* infections were not necessarily disease states. The results were interpreted in terms of the degraded state of the Rottnest vegetation and of the usefulness of the *Salmonella* as indicators of adverse conditions. The position of the Rottnest quokka is believed to have deteriorated greatly in recent times due to the influence of human activities which has resulted in gross changes to the vegetation of the island.

In the study reported here these results have been extended by examining other populations of the quokka where the animals were believed to live under more favourable conditions. The quokka was once widely distributed and common in south-western Western Australia but, following an undocumented catastrophe in the early 1930's, it was believed to have become extinct on the mainland and to have survived on only two small off-shore islands (Rottnest Island and Bald Island, Fig. 1). Subsequently it has been found that the quokka persisted over a wide area of its former range and is now regarded as common but in a much reduced habitat. The quokka on the mainland has been studied by Sadleir (1959) and Shield (1964) who concluded that the animals were in better condition than those on Rottnest and did not suffer the summer decline. Almost nothing is known of the Bald Island quokka. The island is remote and rarely visited due to difficult access so that the vegetation has not been disturbed by human activities (Storr 1965). This paper compares *Salmonella* infections and animal condition of a mainland population and the Bald Island population with those of the Rottnest Island quokkas.

Figure 1.—Map showing locations of the study sites.

Materials and methods

Study sites

A number of mainland sites known to contain quokkas were examined (Fig. 1) and quokka faeces and other specimens were collected and tested for the presence of *Salmonella*. The population at Holyoake (Fig. 1) was selected for an intensive study. This site is typical of the sites now occupied by the quokka, with extremely dense vegetation around permanent water sources. The site was also inhabited by various feral animals (including rats, mice, cats and pigs) and there was agricultural activity upstream from the site so that the quokkas would have been exposed to exotic serotypes of *Salmonella*.

Bald Island has very difficult access and a single one-night trip was made to the island in February 1980. Quokkas are abundant on the island and occur in all vegetation types (Storr 1965).

Animal trapping

Sadleir (1959) trapped quokkas on the mainland and found them extremely difficult to capture. Using box traps and snares he trapped 13 animals from 1 700 trap-nights over 72 days. In order to improve this, elaborate traps were devised for the mainland study site. The traps were modified from a design devised by officers of the Forests Department (Western Australia) and were baited. A fence was built along a path cleared through the area occupied by quokkas. These paths were 20-50m long. Elaborate falling-door traps opening into small enclosures were built on both sides at the ends of the fence with the doors being released by a trip wire. It is not known whether the baiting was important or whether the animals simply followed the fence in their normal movements. With these traps, extensively pre-baited and re-set several times each night, high trap yields were achieved. In November 1976, 100 trap-nights produced 10 animals (10% yield), and in March 1977, 204 trap-nights produced 27 animals (13.2% yield). For these calculations each fence was regarded as four traps. Box traps were also used in March 1977 but no captures were made from 84 trap-nights.

On Bald Island the animals were caught at night with hand nets and spot-lights.

Sampling, isolation and identification of the Salmonella

Salmonella were sought from soils, waters, faeces and rectal swabs. The samples were treated as descibed in Hart, Iveson and Bradshaw (in prep.)

Animal condition

The condition of the quokkas was measured in two ways. Firstly the "Condition Index" of Bakker and Main (1980) was used. This is a body weight index related to the "short leg" measurement and was developed from studies on three macropod species, including the quokka on Rottnest Island. The index is applicable only to adult animals, and males and females cannot be compared directly. Secondly the condition of the animals was assessed by subjective judgment of body fat and skeletal muscle.

Results

The mainland

The *Salmonella* found in samples collected from sites on the mainland other than Holyoake are given in Table 1. *Salmonella* infections are uncommon in these animals and their environment.

At Holyoake where quokkas were trapped, held and tested extensively for several days the results were less clear. In November 1976, 10 animals were captured and no *Salmonella* were isolated. Two serotypes (*S. orientalis* and *S. chester*) were recovered from a large number of environmental samples and none from other species caught in the area. In March 1977, 27 quokkas were captured and *Salmonella* isolations were made from 17 of these individuals at some time. However only two serotypes (*S. muenchen* and *S. newington*) were involved and examination of the timing and distribution of infections between the caged animals suggested that the great majority of the infections resulted from cross infection or cross contamination (see Hart 1980). It is likely that all of the infections resulted from original infections in two or possibly three of the animals. Four isolations were made from environmental samples (one each of *S. muenchen*, *S. give*, *S. orientalis* and an unidentified *Arizona*) and two isolations were made from individuals of *Rattus rattus* caught in the study area (both of *S. muenchen*).

The mean Condition Index from the two samples of animals from Holyoake were not significantly different (t_{14}=0.55, p>0.10 for males and t_{10}=0.053, p>0.10 for females) and the two samples were combined. Two adults were caught in both samples and the pooled sample represented 26 adult animals. These values are compared with values from various Rottnest Island

Table 1

Salmonella isolations from mainland sites. Locations are shown on Fig. 1.

Site, date	Species	Sample	No. of samples	Isolations
Byford, 24.ix.76	Quokka	Pools of faeces	1	—
		Pools of faeces	1	*S. orientalis*
		Pools of faeces	1	*S. newbrunswick*
		Pools of faeces	1	—
		Pools of faeces	1	*S. orientalis*
		Pools of faeces	1	*S. orientalis*
Muddy Lake 24.ix.76	Quokka	Faeces	8	—
	Western Grey Kangaroo (*Macropus fuliginosus*)	Faeces	3	—
19.ii.77	—	Soils	4	—
	Quokka	Faeces	4	—
10.iv.77	Quokka	Faeces	12	—
Mowen/Stoats Rds crossing 26.ix.76	Quokka	Faeces	2	—
	Western Grey Kangaroo	Faeces	2	—
Waychinicup Inlet 27.ix.85	Quokka	Faeces	2	—

Table 2

Condition Index (C.I.) values of Holyoake and Bald Island quokkas, compared with those of Rottnest Island populations in the most favourable season (October/November).

1. Holyoake Mean C.I. Variance Sample size	Significance of difference 1-2	2. Rottnest Island Area Mean C.I. Variance Sample size	Significance of difference 2-3	3. Bald Island Mean C.I. Variance Sample size
A. Males				
7.72 1.01 n=16	$t_{25}=3.69$ $p<0.01$	Settlement 9.17 0.82 n=11	$t_{15}=1.92$ $p<0.10$	9.93 0.669 n=6
	$t_{31}=1.81$ $p<0.10$	Non-lake areas 8.31 0.643 n=17	$t_{21}=4.04$ $p<0.001$	
	$t_{26}=3.68$ $p<0.01$	Barkers Swamp 9.07 0.650 n=12	$t_{16}=2.00$ $p<0.10$	
B. Females				
6.89 0.501 n=10	$t_{14}=2.22$ $p<0.05$	Settlement 7.86 0.84 n=6	$t_{8}=1.36$ $p>0.10$	8.64 0.325 n=4
	$t_{20}=3.35$ $p<0.01$	Non-lake areas 8.06 0.687 n=12	$t_{14}=1.17$ $p>0.10$	
	$t_{22}=1.87$ $p<0.10$	Barkers Swamp 7.51 0.647 n=14	$T_{16}=2.26$ $p<0.05$	

populations at the most favourable season in Table 2, and at the least favourable season in Table 3. The Rottnest populations are discussed in Hart, Iveson and Bradshaw (in prep.). The values from the Holyoake animals are intermediate.

Examination of the short leg measurements from the Holyoake animals shows that the Holyoake animals have longer short leg values (Table 4). The short leg values seen with the Holyoake animals are exceptional by comparison with Rottnest animals. For example, in the sample of only 16 adult males the largest value was 137.5mm, while the largest value measured in the study on Rottnest from a sample of several hundred males was 133mm and values of greater than 130mm (slightly above the average at Holyoake) were rare. These results suggest that there is a morphometric difference and that the Condition Index cannot be used for direct comparison.

The assessment of well-being in the Holyoake quokkas was complicated by serious mortality which occurred in the caged animals in March. In the November study there was no mortality of adult animals although some pouch joeys were lost, presumably as the result of stress on the mother. Seven animals died in the March study of which two were frozen for later study. The timing and distribution of animal deaths was not related to the occurrence of *Salmonella* infections (Hart 1980). The two frozen animals were submitted to a veterinarian for post-mortem examination. Neither specimen was suitable for detailed study but both were diagnosed to

Table 3

Condition Index (C.I.) values of Holyoake animals compared with those of Rottnest animals in the least favourable season (April).

Holyoake Mean C.I. Variance Sample size	Rottnest Area Mean C.I. Variance Sample size	Significance of difference
A. Males		
7.72 1.01 n=16	Non-lake areas 6.25 0.86 n=11	$t_{25}=3.7$ $p<0.01$
	Barkers Swamp 6.92 0.723 n=10	$t_{24}=2.01$ $p<0.10$
	Bickley Swamp 6.13 1.47 n=7	$t_{21}=3.12$ $p<0.01$
B. Females		
6.89 0.501 n=10	Non-lake areas 5.65 0.47 n=5	$t_{13}=3.25$ $p<0.01$
	Barkers Swamp 6.38 0.356 n=11	$t_{19}=1.7$ $p<0.20$
	Bickley Swamp 5.89 0.99 n=7	$t_{15}=2.27$ $p<0.05$

Table 4

Short leg (S.L.) values of Holyoake and Bald Island quokkas compared with those of Rottnest Island populations.

1. Holyoake Mean S.L. (mm) Variance Sample size	Significance of difference 1-2	2. Rottnest Island Area Mean S.L. (mm) Variance Sample size	Significance of difference 2-3	3. Bald Island. Mean S.L. (mm) Variance Sample size
A. Males				
129.6 36.76 n=16	$t_{38}=4.6$ $p<0.001$	Barkers Swamp/Non-lake areas 122.7 9.216 n=24	$t_{28}=3.13$ $p<0.01$	118.2 9.37 n=6
	$t_{37}=2.1$ $p<0.05$	Settlement 125.3 35.28 n=23	$t_{27}=2.76$ $p<0.02$	
B. Females				
118.45 10.97 n=10	$t_{25}=4.0$ $p<0.001$	Barkers Swamp/Non-lake areas 114.3 3.436 n=17	$t_{19}=4.05$ $p<0.001$	110.25 0.917 n=4
	$t_{28}=3.56$ $p<0.01$	Settlement 112.4 21.41 n=20	$t_{22}=0.89$ $p>0.10$	

have died from haemopericardium. Both were judged to be in poor condition on the basis of reduced skeletal muscle, total absence of body fat, and abnormal cardiac muscle. The first animal had been subjected to a heart puncture, but the second had not. At least the second animal died from haemopericardium resulting from abnormal cardiac muscle and probably induced as the result of stress. Three other animals which died were also examined, and these also had no body fat. Although all animals had possibly reduced skeletal muscle, they were not obviously starved and could best be classified as lean.

Bald Island

The *Salmonella* isolations from 14 quokkas captured on Bald Island and 20 fresh faeces collected off the ground are shown in Table 5. In all, 11 (32%) of the 34 samples were positive. In addition to the serotypes isolated from quokkas, nine isolations were made from water samples (four of *S. charity*, two of *S. typhimurium* and one each of *S. carnac*, *S. bovismorbificans* and *S. saintpaul*). Samples from other species produced three other serotypes (*S. panama*, *S. hindmarsh* and *S. muenchen*).

The Bald Island quokkas were clearly in poor physiological condition, with severely-reduced skeletal muscle. However the Condition Index values were higher than any seen on Rottnest (Table 2). Examining the short leg values in comparison with those of the Rottnest animals (Table 4) shows that the Bald Island animals have short leg values below the normal range seen on Rottnest. It is therefore likely that there is a morphometric difference between the populations, and the Condition Index cannot be used for direct comparison.

Table 5

Salmonella isolations from Bald Island quokkas, 13-14. ii. 1980.

Animal	Sample	Isolations
1.	Duplicate swab	—
2.	Duplicate swab	*S. charity*
3.	Duplicate swab	—
4.	Duplicate swab	*S. bovismorbificans*
5.	Duplicate swab	—
6.	Duplicate swab	—
7.	Duplicate swab	—
8.	Duplicate swab	*S. charity*
9.	Duplicate swab	*S. carnac*; S. 6,8:—:—(O Group C_2)
10.	Duplicate swab	*S. bovismorbificans*
11.	Duplicate swab	—
12.	Duplicate swab	—
13.	Duplicate swab	*S.* 6,8:—: (O Group C_2)
14.	Duplicate swab	—
15.	Faeces	—
16.	Faeces	—
17.	Faeces	—
18.	Faeces	*S. merseyside*
19.	Faeces	—
20.	Faeces	—
21.	Faeces	*S. typhimurium*
22.	Faeces	
23.	Faeces	—
24	Faeces	—
25.	Faeces	—
26.	Faeces	*S. carnac*
27.	Faeces	*S. charity*
28.	Faeces	—
29.	Faeces	—
30.	Faeces	—
31.	Faeces	*S. typhimurium*
32.	Faeces	—
33.	Faeces	—
34.	Faeces	—

Discussion

Assessment of the condition of the animals at Holyoake is not clear. Sadleir (1959) found that the mainland animals were in good condition on haematological criteria, and Shield (1964) found that the mainland animals did not show the seasonal anoestrus which is forced on the Rottnest animals by the stressful environment. The results of the present study strongly suggest that the Condition Index cannot be used for direct comparision with the Rottnest animals because of the morphometric difference. Evidence was found that the animals may have an abnormality of the cardiac muscle and a possibly similar condition (myopathy due to vitamin E deficiency) has been described for the Rottnest animals (Kakulas 1961). The almost total absence of body fat in the Holyoake animals is interesting. Rottnest animals have very large fat stores in the most favourable season and Storr (1961) developed a qualitative scale of condition for the Rottnest animals based on fat stores. On this scale the Holyoake animals would be assessed as in poor condition. However, if the Holyoake animals never lay down fat, their lack of fat stores cannot be used as a measure of condition.

The animals at Holyoake were affected by stress in a way which is unknown in Rottnest animals. There is no evidence that this response is important in the normal physiological functioning of the animals and any poor condition was only apparent under the abnormal stress of caging.

Although the Holyoake animals became markedly susceptible to infection under stress, *Salmonella* infections were probably uncommon in wild animals.

On the mainland *Salmonella* isolations from quokkas are uncommon (Table 1). The serotypes present on the mainland include both native and exotic types (see Hart, Iveson and Bradshaw in prep. for a discussion of the serotype groups), and it is likely that the exotic serotypes are widespread but not common in the mainland quokka. *S. newbrunswick*, *S. newington* and *S. give* were the only exotic serotypes isolated from mainland sites. Very intensive searching would reveal further serotypes but the relatively few isolations made at Holyoake despite intensive sampling suggest that the bacteria are present in small numbers and are consequently difficult to detect.

On Bald Island the results were suprisingly similar to those found on Rottnest Island. The animals were in poor condition in summer, although as at Holyoake the morphometric difference prevented the use of the Condition Index. *Salmonella* infections were more common than would be expected for an undisturbed and remote population. Exotic serotypes (*S. bovismorbificans*, *S. hindmarsh*, *S. panama* and *S. typhimurium*) represented a significant part of the serotype range. The Bald Island quokkas suffer some form of gross starvation in summer and this is likely to be due to a summer decline in the nutritive quality of the vegetation as has been described on Rottnest. The climate on Bald Island is essentially similar to that of Rottnest with a long hot summer, however the vegetation of Bald Island has not been subjected to the catastrophic changes seen on Rottnest. The frequency of *Salmonella* isolations suggests that the animals are in a position intermediate between that of the Rottnest animals (where *Salmonella* infections are virtually ubiquitous in summer) and of the mainland animals.

Bald Island has no introduced vertebrates and there has been very little human activity, although sheep have been released on the island on at least one occasion (Hart 1980). Seabirds are the only other possible vector. These results raise the possibility that the Rottnest quokka experienced a summer starvation and *Salmonella* proliferation before the effects of European settlement. The proliferation of *Salmonella* on Bald Island would appear to be the result of the susceptibility of the quokka to infection during the summer starvation. Since the vegetation of Bald Island is undisturbed a similar situation was likely to have existed on Rottnest before European settlement. Only native serotypes would have been involved at that time.

Both the Rottnest and Bald Island populations are isolated remnants trapped on islands by the rising sea level at the end of the Pleistocene and it is possible that they are now surviving in habitats which are not favourable to them. The quokka is the only native terrestrial mammal on both of the islands and in the absence of predators it is likely that the populations are controlled by food supply in conjunction with behavioural spacing mechanisms. Rottnest was isolated from the mainland as recently as 7 000 years ago (Churchill 1959), and Bald Island 10 000 years ago (Storr 1965). From the physical differences it would appear that these populations have diverged significantly in that time. If both populations have been subjected to regular summer starvation and consequently heavy selection pressure in the absence of predators it is possible that this has been sufficient to cause these changes in the populations.

The presence of large fat stores in the Rottnest quokka but not the mainland animals suggests that the Rottnest animals have adapted to regular starvation. It is not known if the Bald Island animals lay down fat stores during winter and spring. On Bald Island only four adult females were captured but none of these had pouch young. Four juveniles were captured and these were all of a similar age with short leg values at 90-96mm. It is possible that the Bald Island animals have seasonal breeding like the Rottnest animals.

On the mainland the situation is quite different to that seen with the two island populations. Although the animals may not be as well off as previously believed, it is clear that any physiological difficulties are not like those of the island populations. Exotic *Salmonella* serotypes are probably widespread in the environment but the quokkas are not readily susceptible to infection, and the *Salmonella* would normally be present in only small numbers.

These results give further support to the proposal by Hart, Bradshaw and Iveson (1985) that the *Salmonella* are useful indicators of stress in wild animals.

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The effects of urbanization on the ant fauna of the Swan Coastal Plain near Perth, Western Australia

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Abstract

The ant fauna in 33 Perth gardens was surveyed by hand collecting and pitfall trapping. The resulting catch was considered at the species level and also four ant variables (abundance, species richness, species diversity and species evenness) were investigated for correlation with garden botanical and management variables.

Forty-seven ant species from 22 genera were recorded from the gardens. Thirty-six species occurred in less than one third of the gardens which were studied. Some of the species were absent or uncommon in adjacent native vegetation indicating that they were favoured by urbanization while other species from the native vegetation were unable to colonize, or persist in, the gardens.

Ant species richness and diversity were significantly lower in gardens than native vegetation while species evenness did not statistically differ between the two types of land use. The ant fauna was enhanced by the length of time the garden had been established, and also increased garden area, leaf litter and ground cover. Gardens where pesticides were used, where tall shrubs were dense or where management (e.g. watering) was intense, had a depauperate ant fauna.

This study has indicated that urban gardens are an important refuge for ants and maybe, because ant species richness often reflects that of other invertebrates groups, for a wide range of other invertebrates.

Introduction

With the rapid expansion of towns and cities in Australia the role of urbanized areas as wildlife refuges has become crucially important. The interest in such areas as wildlife refuges is illustrated by the Brisbane Wildlife Survey (Davies 1983) which documented the butterflies, fish, amphibia, reptiles, birds and mammals of Brisbane's suburbs and emphasised the importance of urban areas for a wide range of fauna.

Native vegetation and agricultural land are rapidly being transformed into urban areas in Perth, Western Australia. This has led to recommendations for the establishment of a series of parks and reserves in what is referred to as the Darling System of land which envelopes, and includes, the Perth Metropolitan area (Anon. 1981).

The ant fauna of the Swan Coastal Plain, close to Perth, has been documented by Rossbach and Majer (1983). Their survey was confined to pristine habitats and showed that the ant fauna of the open-forests and woodlands of the Coastal Plain was reasonably distinct from the fauna of the coastal scrub close to the ocean, or the open-forest of the Darling Plateau.

The present survey extends this work by investigating the influence on the ant fauna of progressive urbanization of open-forests and woodlands of the Swan Coastal Plain.

Methods

Description of gardens

Thirty-three gardens, representing 25 suburbs, within a 20 km radius of the Perth General Post Office, were selected for study. Selection was partly governed by the availability of volunteer participants in the project, although it was also influenced by the need to include a full age-range of suburbs.

Measurements and observations were made in each garden to describe its flora and the type of management that it had been subjected to. Variables were quantified by visually inspecting gardens during December 1982, by interviewing the home occupants and by consulting maps:

Soil association and vegetation system—The landform and soil association on which each garden occurred was assessed by locating each garden on the System 6 landform and soil map of Churchward and McArthur (1980). The vegetation system which occurred prior to urbanization of Perth was assessed from the System 6 vegetation association map of Heddle *et al.* (1980). The different soil associations, which were all sandy, and vegetation systems which were included in this study are shown in Table 1.

Age—Two ages were recorded. The first, location age, was the age of the residence and was presumed to reflect the period of alienation of the area from the original native vegetation. All residences were assumed to have been built after the areas had recently been cleared, although the possibility that some gardens had previously been cleared for agricultural purposes cannot be excluded. Location ages were categorized as: 1, 0-6 years; 2, 7-13 years; 3, 14-30 years; 4, 31-50 years; or 6, >51 years. The second, garden establishment age, was the age of the existing garden, since gardens may go through a series of changes depending on the requirements of the owner. It was not possible to be as specific as with location age, so the following four categories were selected: 1, 0-4 years; 2, 5-8 years; 3, 9-14 years; or 4, >15 years.

Area of garden—This was the area of the block minus the area taken up by the house, patio or other out-buildings.

Floristics—Each garden was categorized according to the emphasis on exotic or native Western Australian plants. Five categories were used to illustrate this: 1, totally native vegetation; 2, mostly native species; 3, an approximately equal mixture of native and non-native species; 4, mostly non-native species; or 5, totally non-native species. Gardens were also rated as having a: 1, low; 2, intermediate; or 3, high plant species richness, regardless of whether the species were native or non-native.

Vegetation structure—This was described using an estimate of plant biomass on a four-point scale: 1, very little plant biomass; 2, low biomass; 3, intermediate biomass; or 4, densely planted gardens, with high biomass. In addition, percentage cover of vegetation was visually assessed and assigned to one of five percentage cover categories: 1, absent; 2, 1-10%; 3, 11-25%; 4, 26-50%; or 5, >51%. Vegetation cover was independently assessed for herbs plus low shrubs (<2 m tall), tall shrubs (2-10 m tall), trees (>10 m tall) and all strata combined.

Leaf litter—Leaf litter on garden beds was categorized as: 1, dense and present over most of soil; 2, thin and sparse; or 3, absent.

Lawn—This was categorized as: 1, absent; 2, unmaintained lawn; 3, well covered lawn; or 4, lush, well-maintained lawn.

Pesticide usage—By interviewing occupants, it was possible to assign gardens to one of four pesticide use categories: 1, no pesticide used; 2, pesticides occasionally used to control plant pests; 3, occupant has attempted to control house infesting ants; or 4, garden treated with Heptochlor by Department of Agriculture to control argentine ants (*Iridomyrmex humilis*).

Watering regime—Gardens were categorized by watering regime as follows: 1, watered less than once per week; 2, watered at least one or two times per week; or 3, watered at least once every 2 days.

Ant sampling procedure

Ants were sampled by hand collection conducted by residents on an opportunistic basis during autumn and winter, 1982 and by pitfall trapping during December, 1982. Ten pitfall traps (18mm internal diameter, containing a 70/30 v/v mix of ethanol/glycerol preservative) were inserted within each garden. The traps were subjectively arranged so that they sampled each particular type of vegetation represented in the garden. At least one trap was always placed in the lawn. Traps were left out for 7 days and then returned to the laboratory where the catch was sorted.

All ants were sorted to species level and, where possible, named. Some of the species names given in this paper apply only in a very broad sense and therefore identify what are often species complexes. Unnamed species were coded with Australian National Insect Collection (ANIC) or Western Australian Institute of Technology (J.D.M.) code numbers, which conform to the nomenclature used by Rossbach and Majer (1983). Voucher specimens are retained at the Western Australian Institute of Technology.

Data analysis

Four ant parameters were calculated for each garden: (1) Ant abundance was derived by summing the number of ants caught in the 10 pitfall traps; (2) Ant species richness in gardens was derived by summing the total number of species obtained by both sampling methods; (3) The Shannon's diversity index, H' (Shannon and Weaver 1949) was applied to the pitfall trap data as a measure of species diversity; and (4) ant evenness was calculated using the formula:

$$J' = \frac{H'}{\log S}$$

where S is the total species present.

A correlation matrix was calculated in order to investigate the relationship between the various ant variables and garden parameters. The Pearson correlation was used for continuously distributed variables and the Spearman rank correlation was used for those variables measured on the discrete 3 and 5 point scales. From this matrix a constellation diagram of correlated factors was constructed, incorporating only those pairs of variables that were significantly correlated with each other. Correlation does not necessarily imply cause and effect, since inter-correlations between variables may suggest relationships which are in fact spurious, or may mask the causal effects of other variables. Although not providing conclusive evidence, the correlations do give some idea of the influence of garden history and management variables on the four ant variables under investigation.

Table 1

Landform and soils and also vegetation systems occurring in areas where the 33 gardens used in this survey occurred.

Landform & Soils From Churchward and McArthur (1980)	Vegetation System From Heddle *et al.* (1980)
Bassendean	Bassendean Complex—Central and South
Cottesloe	Cottesloe Complex—Central and South
Herdsman	Guildford Complex
Karrakatta	Karrakatta Complex—Central and South
Southern River	Quindalup Complex
Swan	Swan Complex
Vasse	Vasse Complex

Results

The species of ants found in this survey and the percentage of gardens in which they were present are shown in Table 2. Forty-seven species from 22 genera were recorded in gardens. The most common species, listed in decreasing order of frequency, were *Iridomyrmex* sp. JDM 9, *Iridomyrmex* sp. 21 (ANIC), *Pheidole latigena*, *Cardiocondyla nuda*, *Iridomyrmex* sp. JDM 83, *Adlerzia froggatti*, *Tetramorium bicarinatum*, *Brachyponera lutea*, *Pheidole* sp. JDM 44, *Pheidole* sp. JDM 177 and *Paratrechina* sp. JDM 339. The remaining species occurred in less than one third of the gardens.

Twenty-four (51%) of the garden ant species were not recorded by Rossbach and Majer (1983) indicating that many are favoured by the urbanization process. It is interesting to note that only five of the frequently occurring ants listed above are included in the confined-to-gardens category (*Adlerzia froggatti*, *Pheidole* sp. JDM 44, *Pheidole* sp. JDM 177, *Tetramorium bicarinatum* and *Paratrechina* sp. JDM 339), the remainder were also

Table 2

List of ant species found in the 33 Perth gardens sampled in the Perth metropolitan region showing the percentage of gardens in which each species occurred.

Sub-family	Species	Gardens where present																																	Percentage of gardens where species present
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	
PONERINAE	Brachyponera lutea		+	+	+			+								+		+	+		+						+	+		+		+	+		39
	*Hypoponera sp. JDM 165	+							+		+														+	+	+						+	+	24
	Rhytidoponera inornata				+								+		+	+										+	+			+					21
	R. violacea			+							+																					+			9
MYRMICINAE	*Adlerzia froggatti	+			+				+		+	+		+	+	+			+		+	+		+						+	+		+		46
	*Anisopheidole antipodum					+									+	+								+						+					15
	*Aphaenogaster sp. JDM 224																															+		+	6
	Cardiocondyla nuda		+	+	+	+	+	+	+		+	+	+	+		+	+	+	+			+	+		+	+	+	+		+	+	+		+	76
	*Chelaner sp. JDM 61																															+			3
	Crematogaster sp. JDM 33								+		+				+	+			+							+					+	+			24
	C. sp. JDM 350															+																+			6
	Meranoplus sp. JDM 157															+																			3
	*M. sp JDM 158															+																			3
	Monomorium sp. 1(ANIC)												+																					+	6
	M. sp. 2(ANIC)		+		+								+			+		+														+			18
	M. sp. JDM 156												+																						3
	Pheidole latigena	+	+	+	+	+	+	+	+	+	+			+	+	+	+	+	+		+	+		+		+		+	+	+	+	+		+	79
	*P. sp. JDM 44	+					+			+	+	+		+			+		+				+		+						+				33
	*P sp. JDM 177	+								+	+	+					+	+	+					+		+					+			+	33
	*Solenopsis sp. JDM 34		+				+	+	+		+	+						+	+		+									+					30
	*Tetramorium bicarinatum		+	+	+	+		+	+		+		+		+				+								+	+				+		+	42
DOLI-CHODERINAE	*Iridomyrmex darwinianus												+							+															6
	I. purpureus		+	+		+		+																	+		+	+				+			24
	I. sp. 21(ANIC)		+	+	+	+	+	+	+		+	+		+	+		+	+	+	+	+	+	+	+	+	+	+		+	+	+	+		+	82
	I. sp. JDM 9	+	+	+	+	+	+	+	+	+	+	+	+	+		+	+	+	+			+	+	+		+	+	+		+	+	+	+	+	85
	I. sp. JDM 83				+	+	+	+	+	+	+	+	+		+		+	+		+		+			+					+	+	+	+	+	61
	*I. sp. JDM 172												+														+								6
* * *	I. sp. JDM 509																																	+	3
	*I. SP. JDM 625																		+									+							6
	Tapinoma sp. 134														+	+																			6
	*Technomyrmex sp. JDM 624	+							+	+																									9
FORMICINAE	Camponotus sp. JDM 25																																+		3
	C. sp. JDM 27					+						+																		+		+	+		15
	*C. sp. JDM 63													+																					3
	*C. sp. JDM 110				+											+			+				+									+			15
	*C. sp. JDM 183								+	+			+																	+					12
	C. sp. JDM 199														+							+		+								+			12
	C. sp. JDM 359								+		+			+	+																		+		15
	*C. sp. JDM 364																															+			3
	Melophorus sp. 1(ANIC)			+			+				+					+			+	+	+														21
	M. sp. 3(ANIC)															+														+					6
	M. sp. JDM 221															+																			3
	Notoncus gilberti							+								+								+								+		+	15
	*Paratrechina sp. JDM 147																																+		3
	*P. sp. JDM 339					+	+		+	+	+												+		+		+		+				+	+	33
	*Stigmacros sp. JDM 113			+																												+			6
	*S. sp. JDM 195								+							+																			6

*Denotes those species not recorded by Rossbach and Majer (1983).

found in native vegetation. The number of species in the confined-to-gardens category may be inflated by the presence of uncommon species which are only occasionally sampled in a habitat, even if they are actually present. Also, garden species which are absent from the open-forests or woodlands of the Coastal Plain may be present in other vegetation associations. *Aphaenogaster* sp. JDM 224 and *Tetramorium bicarinatum*, for instance, were respectively found in the closed scrub of the Coastal Plain or the open-forest of the Darling Plateau by Majer and Rossbach (1983).

Of the 60 species from 19 genera sampled in woodlands and open-forests of the Coastal Plain by Rossbach and Majer (1983), 37 were absent from the gardens which were sampled. These species were either uncommon, and hence missed in garden samples, or were unable to withstand urbanization. The remaining 23 species found by Rossbach and Majer in woodlands or open-forests of the Coastal Plain were also present in gardens.

Species richness varied from 3-20 ($\bar{x}$ = 9.8), compared with 17-29 ($\bar{x}$ = 22.8) for the native vegetation sites (Rossbach and Majer 1983) and these means were significantly different (t = -8.54, $p<0.001$). Species diversity varied from 0.28-0.92 ($\bar{x}$ = 0.57) in comparison with 0.62-1.04 ($\bar{x}$ = 0.80) for the native vegetation sites. These means were significantly different (t = -3.57, $p<0.001$). Species evenness values varied from 0.33-1.00 ($\bar{x}$ = 0.64) in the gardens, and these did not differ significantly from those in native vegetation (0.49-0.75, $\bar{x}$ = 0.62).

The ant abundance, species richness, diversity and evenness variables were, to a large extent, intercorrelated (Figure 1). Ant abundance was positively associated with total ground cover and the amount of leaf litter but negatively associated with tall shrub cover. Both ant species richness and diversity were positively correlated with the area of the garden and the garden establishment age but negatively correlated with pesticide usage and the watering regime. The amount of leaf litter was also positively correlated with ant species richness while ant evenness was negatively correlated with herb and low shrub cover.

Discussion

This study has revealed the existence of a rich and varied ant fauna in Perth's gardens. It appears that many of these species are favoured by the urbanization process, whilst other native species are unable to colonize or persist in gardens.

The ants recorded in gardens and native woodlands or open-forests of the Coastal Plain are compared in terms of Greenslade's community structure categories (see Greenslade and Thompson 1981) in Table 3. The structure of the garden ant fauna differs from that in adjacent native vegetation in a number of ways.

First, the domination of the fauna by *Iridomyrmex* spp. (Group 1a) is proportionally less in gardens than in native vegetation. The most common species in gardens (*Iridomyrmex* sp. 21 (ANIC), *Iridomyrex* sp. J.D.M. 9 and *Iridomyrmex* sp. J.D.M. 83) are all species which abound in disturbed habitats but which are not necessarily the dominant species in native vegetation (Rossbach and Majer 1983).

Second, there are fewer climate specialists (Group 3a), such as *Meranoplus* spp. and *Melophorus* spp. in gardens than in native vegetation. *Melophorus* spp. tend to avoid unstable sandy soils (P.J.M. Greenslade, personal communication), such as those found in many Perth gardens, while *Meranoplus* spp. may be responding to the paucity of seed diet in gardens.

Table3

Summary of the structure of the ant communities associated with gardens and with native woodlands and open-forests of the Swan Coastal Plain. The ants are classified by the scheme described in Greenslade and Thompson (1981); numbers and bracketed numbers respectively represent the total and percentage total species in each category.

	Gardens	Native vegetation
1a) Dominant epigaeic Iridomyrmex	7 (15)	12 (22)
1b) Other epigaeic Dolichoderinae	1 (2)	1 (2)
2) Subordinate Camponotus	8 (17)	9 (15)
3a) Climate specialists	6 (13)	15 (25)
3b) Soil specialists	3 (6)	2 (3)
4) Cryptic species	8 (17)	5 (8)
5) Opportunists	5 (11)	3 (5)
6) Generalized myrmicines	9 (19)	11 (18)
7) Large solitary foragers	0 (0)	2 (3)
Total species	47	60

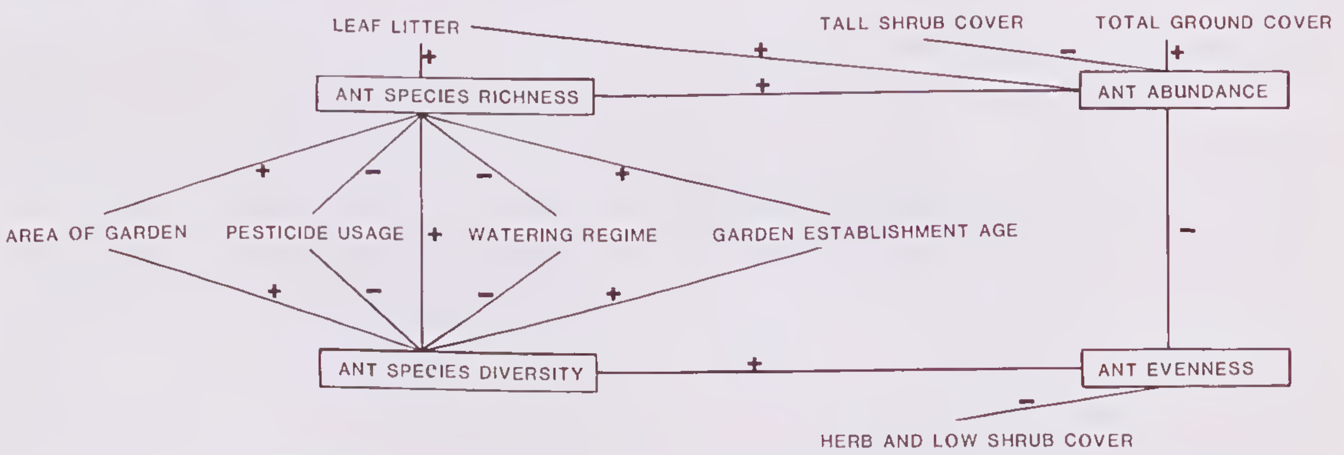

Figure 1.—Diagram of garden variables which were positively ($p < 5\%$) correlated with at least one of the four ant variables. Statistics used were the Pearson correlation for the continuous variable data and the Spearman's rank correlation for the discrete variable data.

The next obvious difference is the relative abundance of cryptic species (Group 4) in gardens. This may be related to the build up of dense litter loads in some of the older gardens although the abundance of *Adlerzia froggatti*, a species which was not found in native vegetation (Table 2), may be caused by reduced competition from dominant *Iridomyrmex* spp. in gardens. Andersen and Yen (1985) have noticed that this genus increases after fire at a time when dominant *Iridomyrmex* populations are severely depleted by the effects of the fire.

Opportunistic species (Group 5), such as *Rhytidoponera* spp., *Cardiocondyla nuda*, and *Paratrechina* spp. were also proportionally more abundant in the gardens. The former two genera are also early colonizers of the early rehabilitated bauxite mines (Majer *et al.* 1984) and their opportunistic characteristics well suit them to the disturbed nature of the gardens. Also, *Cardiocondyla* and *Paratrechina* are genera of tropical origin which may benefit from the high temperatures on the bare ground in some gardens and also from reduced competition with dominant *Iridomyrmex* spp. This may also explain the abundance of *Technomyrmex* sp. (Group 1b) in some of the gardens.

The final contrast in the gardens is the absence of large solitary foragers such as *Myrmecia* spp. This may reflect the fact that these species tend to be poor colonizers (see Majer *et al.* 1984) and also that householders often attempt to eradicate large conspicuous species.

The results of the correlation analysis suggest that the development, or retention, of the ant fauna is likely to be favoured by a number of garden management practices such as the creation of dense ground cover, thick leaf litter and gardens of moderate size.

The positive correlation of ant species richness with garden age is of interest as it suggests that there is a build up of the ant fauna with increasing age of the garden. When new homes are established the garden area is generally cleared in preparation for home construction or the planning of a garden of the type required by the occupant. There subsequently follows a build up in the complexity and maturity of the garden. The oldest gardens (8, 12, 15, 17 and 29) contained a number of cryptic or specialized species such as *Meranoplus* spp., *Tapinoma* sp. J.D.M. 134, *Iridomyrmex darwinianus*, *Melophorus* sp. 3 (ANIC) and *Stigmacros* sp. J.D.M. 195 which were absent, or infrequently found, in the younger gardens. These were probably associated with the build-up of leaf litter, tall shrub cover, tree cover and plant species richness, which were all significantly positively correlated with garden establishment or location age. Species richness in the older gardens approached that of the native vegetation (up to 20 species). By contrast, however, a number of the species in these gardens were opportunistic species which are absent or uncommon in native vegetation (e.g. *Cardiocondyla nuda* and *Paratrechina* sp. J.D.M. 339).

A number of factors appeared to diminish one or more of the four ant variables which were investigated. The increased watering regime was positively correlated with a number of other parameters such as lawn condition, and these gardens tended to have large areas devoted to lawns which were tidy with well weeded beds. It may well have been these intensive management practices which led to the simplified ant fauna in such areas.

The degree of pesticide usage was, not surprisingly, associated with a simplified ant fauna. This may have operated directly first, and then indirectly via the depletion of Homoptera sap sources in gardens where pesticides were used (Czechowski 1980) or via the direct impact of pesticides on ants. For instance, garden 19 had been sprayed with Heptachlor in order to eradicate argentine ants *(Iridomyrmex humilis)* just prior to the survey and only four ants were recorded here.

The reduced ant abundance under tall shrup cover was probably associated with the consequent dense shade and lower temperatures, conditions that are likely to reduce ant activity (Brian and Brian 1951, Greenslade 1979).

The reason for the low ant evenness values under dense herb and low shrub cover is not immediately obvious. Possibly it is caused by dense coverings of individual plant species which reduce the patchy nature of the garden and hence the opportunities for persistence of a wide range of ant species.

There is evidence that the richness of the ant fauna is positively correlated with certain other intervertebrates taxa such as collembolans and termites (Majer 1983). It therefore follows that gardens with a rich ant fauna may also harbour a wide variety of other invertebrates. This study has indicated the value of gardens as a refuge for native ant species and possibly also for many other insect groups. It is encouraging to see that older established gardens harbour such a variety of ant species. This suggests that the conservation value of Perth's gardens may improve with the passage of time.

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Air pollution components in Perth

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Abstract

High volume dust sampling, SO_2, NO_x, and fine particle mass concentration (FPMC) measurements were performed at 23 sites around the city of Perth. The dust samples were analyzed by atomic absorption techniques for the elements Ca, Cu, Pb, and Zn; flame photometry was used for Na and K. The emissions from possible sources of pollution, such as petrol engines, coal furnaces, hospital incinerators, cement works and bush fires were analyzed for the same elements. Results show that the strong lead (Pb) peak in the city centre is related to high density car traffic, as the combustion of petrol is the dominant source of lead. The levels for SO_2 and NO_x were generally low but showed some increase in the central business district. Comparatively higher calcium peaks in the south west and north west of the area may be associated with cement works and brickworks respectively.

The concentrations did not reach levels considered as being harmful to man and his environment, but meteorological patterns and traffic conditions in Perth indicate that it is necessary to monitor the contamination in the air now. This would enable appropriate controls to be developed for implementation before the effects resulting from a growing population push pollution to unacceptable levels.

Introduction

As cities grow, so does air pollution for many reasons (Williams *et al.* 1981). Petrol and diesel vehicles are major contributors; in addition there is power generation from coal and wood and industrial wastes. Furthermore incinerator burning, bush fires and burning off, all increase the level of air pollution. A general increase in the number of suspended inorganic particles may be caused by increased construction activity.

Perth, on the western seaboard of Australia, is no exception and with a population now topping the million mark, air pollution could eventually become a serious problem, unless steps are taken to control the most serious sources. Situated as it is on the coastal plain beneath the Darling Scarp, early morning temperature inversions make it possible for the Perth haze to become clearly visible. Fortunately, the city is commonly ventilated by sea breezes later in the day.

No studies have been undertaken on the problem of air pollution as a whole in Perth, although a number of projects have investigated particular aspects of it. Bottomley and Boujois (1975) examined the amount of lead in the soil of Heirisson Island, and found that the concentration decreased with distance from the highway. Bottomley and Cattell (1975) also studied the nitrogen oxide levels in the Perth suburbs and observed peaks that were related to car traffic. They were also able to observe a mild formation of photochemical smog. Pb concentrations monitored over a three year period (O'Connor and Allen 1980) indicated that the change in mean seasonal levels was similar for a central and a suburban site. The amount of airborne lead correlated well with ventilation parameters over quarterly periods. Maximum Pb values occurred in winter. Low levels of paticulate matter were found by O'Connor *et al.* (1981) in two suburban stations, whereas the measurements were definitely higher near Kwinana. A major research project, the Kwinana Air Modelling Study (1982), detailed the effect of Perth's industrial complex on the air pollution of the surrounding area, and developed models relating pollution levels to different meteorological conditions and source emissions.

More recently Watson (1984) investigated the buildup of carbon monoxide aside the Kwinana Freeway and showed the important effect of atmospheric stability in the dispersion of pollutants.

An attempt to study variations in the quality of the air in Perth was undertaken by Robertson *et al.* (1985). The relation of pollution to sources was considered using elements as fingerprints. Relatively high lead levels were measured in the central business districts. The mass of particles was low in the suburbs and semi-industrial areas sampled.

The possibility of tracing sources using fingerprint-elements has been shown by the work of Gatz (1975) in Chicago. It is noteworthy that tracer influences can be complex and variable.

The present work was designed to assess the variability of the sources, such as petrol engines and bush fires, as well as to monitor the extent of the dispersion of the pollution to the surrounding environment.

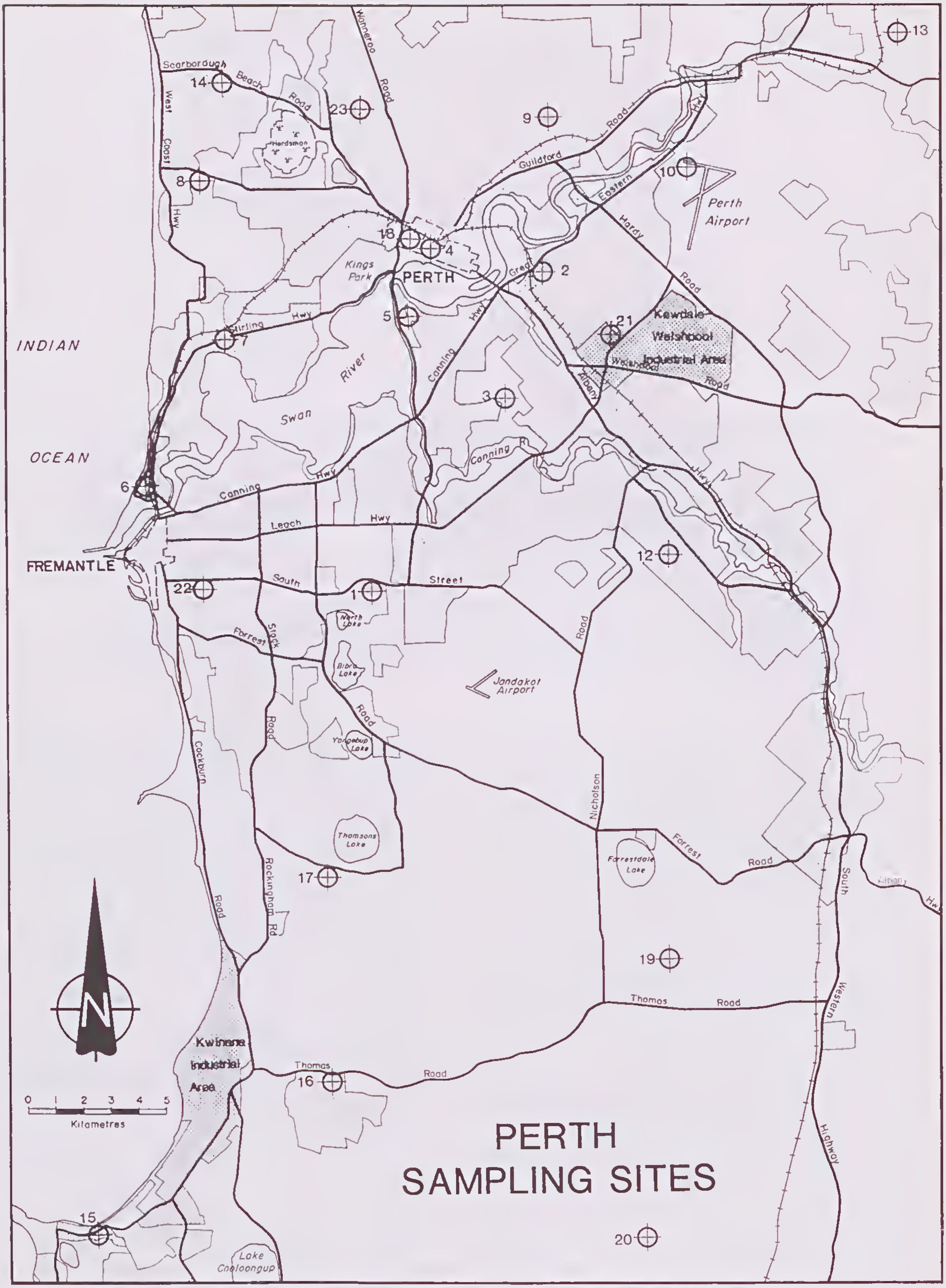
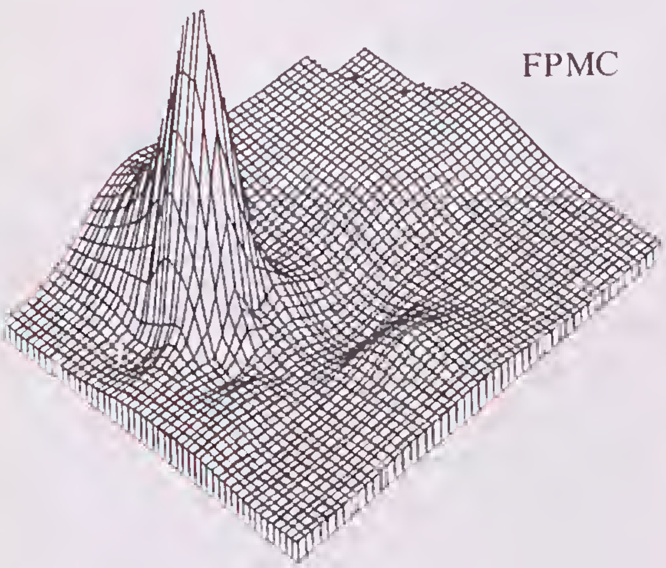
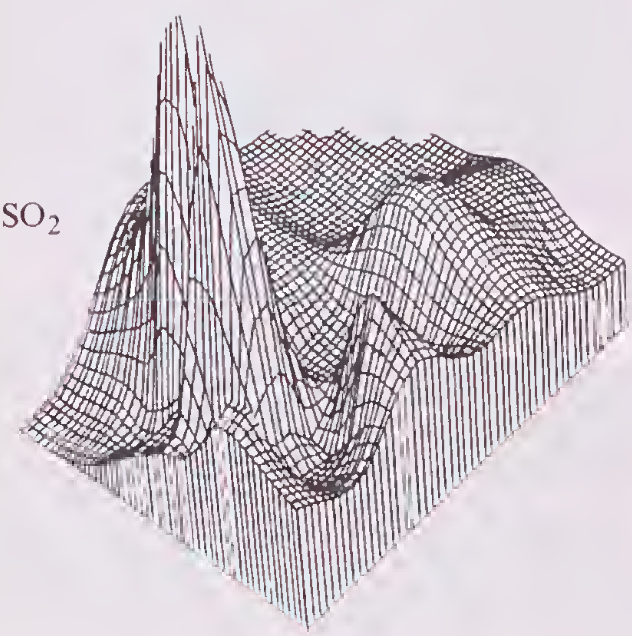


Figure 1.—Map of the area showing the sampling sites. Suburban areas have stippled and industrial areas shown in heavy stipple.

Perth, the capital of Western Australia, has little heavy industry with its light industry scattered over a wide area, commonly adjacent to garden, dormitory suburbs. The heavy industrial area is at Kwinana, 30 km south-southwest from the city centre (see Figure 1). At Kwinana nickel and aluminium smelters, oil refineries, chemical plants, and power stations contribute to air pollution.

The katabatic easterly winds characteristic of early summer mornings tend to carry the effluent from Kwinana out to sea. Later the sea breezes from the west and south-west may bring the odour of the Kwinana industrial area with them, particularly to Fremantle. The strong breezes of summer, which are a feature of the local weather, tend to disperse the industrial pollution and the rains of winter act as a scrubber. However, the alternation of katabatic winds from the east and westerly seabreezes, at times cause the same parcel of air to return to the city.





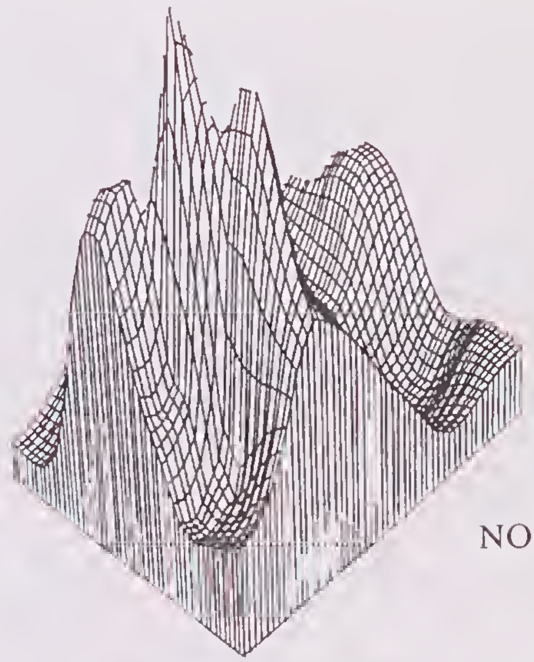


Figure 2.—Topograhy of the concentration distribution for fine mass particle concentration (FPMC), sulfur dioxide (SO_2), and total nitrogen oxides (NO_x) in Perth, viewed from the north-west, the area depicted corresponds with that on Figure 1.

There are times during the equinoxes and also the summer when a brown haze develops. Pollution from industry undoubtedly contributes to this haze, but much of it is generated by the exhaust from motor vehicles. Perth has more motor vehicles per head of population than any other city in Australia. Perth also boasts the highest emissions (HC, CO, NO_x, Pb) per person of any Australian city (Kenworthy and Newman 1984).

Material and methods

Sampling sources

Pollutants of various sources were sampled using Whatman 41 filter papers in a fixed flow sampler placed at a "convenient" distance from the source. In the case of petrol and diesel motors this was one metre behind the exhaust outlet. Bush fire smoke was sampled from a distance of about 10 m. Particles emitted from cement works, brickworks, and power stations were sampled from the stack. The concentration of the exhausts sampled was not uniform, and the very high values of trace elements obtained from the cement works and the hospital incinerator are due to higher concentrations at the sampling port.

Another very important source along the coast, which was not sampled, is the ocean, a major source of sodium and to a lesser degree potassium and calcium (Ratio Na:K:Ca = 25:1:1).

Sampling ambient air

The sampling was performed sequentially at 23 sites (see Figure 1) during the Summer of 1985 between mid January and mid March. At each site the apparatus was run for 24 hours, to include a diurnal cycle. Sites were chosen to give a wide area coverage of the city, including as great a variety of different environments as possible.

The same set of instruments was set up at each site. A nephelometer was used to measure the light scattering due to particles, a high volume sampler collected suspended dust, SO_2-concentrations were obtained by batch absorption method (physico-chemical analytical procedure), and a similar absorption method was applied to measure the concentration of NO_x

A nephelometer (Ahlquist and Carlson 1976) was used for the fine particle mass concentration (FPMC). In principle the integrating nephelometer uses the method of light scattering, where air is drawn through a chamber in which the integrated light scattering coefficient (b_{scat}) is measured (Heggie and Hawke 1984). The wavelength used (525 nm) is appropriate for the fine particles. The scattering coefficient is measured by illuminating a sample of air and detecting the amount of light scattered over a wide angle. Particles in the 0.2-1 μm range of diameter are the most efficient at scattering light (Waggoner *et al.* 1981).

To negate the effects of atmospheric moisture a sample air inlet heater was used, equipped with a temperature control circuit to prevent alteration of the aerosol due to excessive heat.

The analog output of the nephelometer was connected to an analog-to-digital converter and the data were stored by a real time data logging system (NEC PC-8201A). One value was read every second. The mean, the standard deviation, the maximum and the minimum value were calculated by the microprocessor at ten minute intervals and stored.

The calculation of FPMC using the b_{scat} values requires some knowledge of the chemical and physical structure of the aerosol (Heggie and Hawke 1984). In the absence of such detailed information, the approximate formula from the nephelometer manual (Meteorology Research Inc. 1979) may be used:

$$FPMC = 0.38\ b_{scat} g\ m^{-3}$$

Standard high volume samples were obtained using a unit manufactured by Control Engineering Services. The samples were obtained by drawing air at a rate of 60 m^3 per hour through a cellulose filter paper. This Whatman 41 filter was chosen for its low content of trace elements. It was found in earlier studies (Robertson *et al.* 1985), that silica based papers contain unacceptabily high amounts of potassium and calcium, two elements under study. The samples were processed by dissolving the filter papers in a nitric acid solution, which was subsequently filtered and analyzed.

The metal components of each solution were determined by atomic absorption spectroscopy. The absorbance of each sample was compared to that of standard metal solutions. Copper, lead and zinc needed no additional pre-treatment and were read directly using the air/acetylene flame. Calcium solutions, however were aspirated in a nitrous oxide/acetylene flame and required the addition of potassium in order to overcome ionisation interference. Sodium and potassium were determined from the solutions by standard flame photometric emission techniques.

The concentration of SO_2 and NO_x in the air was determined by drawing air through chemical solutions in absorbers; the solutions react with the gaseous pollutants. The solution used for absorbing the SO_2 was potassium tetrachloromercurate (TCM), which resists oxygenation in the air. Thereafter the complex reacts with pararosaniline and formaldehyde to form intensely coloured pararosaniline methyl sulfonic acid. The absorbance of the solution was measured photospectrometrically (548 nm with an effective spectral bandwidth of less than 15 nm) (see Scaringelli *et al.* 1967).

Nitrogen dioxides were collected by bubbling air through a potassium permanganate solution in series with a sodium hydroxide solution to form a stable solution of sodium nitrite. The potassium permanganate solution was used to oxidize the NO to NO_2. The nitrite ion produced during the sampling is determined colorimetrically by reacting the exposed absorbing reagent with phosphoric acid, sulfanilamide and N-1 naphtylenediamine dihydrochloride (Huygen and Steerman 1971).

Meterorological data for this period were obtained from a central weather station and related to the measured concentrations.

The effect of the weather

The weather at the time of sampling can have an important effect on dust sampling. The greater the turbulence, the more dispersed the dust becomes. The nearest wind measurements were taken from the Perth airport records; Table 6 gives a summary of the wind conditions. During a single day the wind velocity ranged widely, with most days containing periods of calm and other periods of fresh breezes. The maximum windspeed during sampling at the sites varied by a factor of 2 and the mean values by a factor of 4.

The predominant wind direction throughout January was from the south west, whereas during February and early March winds from the south and east were also common. The winds displayed the typical summer pattern for most of the survey, with morning easterlies giving way later in the day to sea breezes from the south west. The mean temperatures were high in January, building up to a climax through February (see Table 2). This consistent summer pattern made the sampling conditions similar for most of the 24 hour periods over which each site was sampled, even though comparative data of single days is subject to a high possibility of interpretation error. This limits the accuracy of the graphical display of the areal distribution for the trace-element distribution, FPMC, SO_2, and NO_X in the contour and surface plots (Figures 2 and 3).

Results

The trace-element results for the sites are shown in Table 1 and Figure 3. The most obvious causal relationship appears between lead and the CBD area. Judging by the high lead concentrations in the petrol engine sources (Table 4), the CBD lead pollution can be attributed to contamination from the exhausts of petrol engines. This should be reduced as legislation comes into effect (as the cars complying with ADR 37 running on unleaded petrol come in wider use). The CBD is the only area which exceeded 1.5 $\mu g\ m^{-3}$ on the day of sampling, but Raven and O'Connor (1985) measured Pb-levels up to 3 $\mu g\ m^{-3}$ in the winter period.

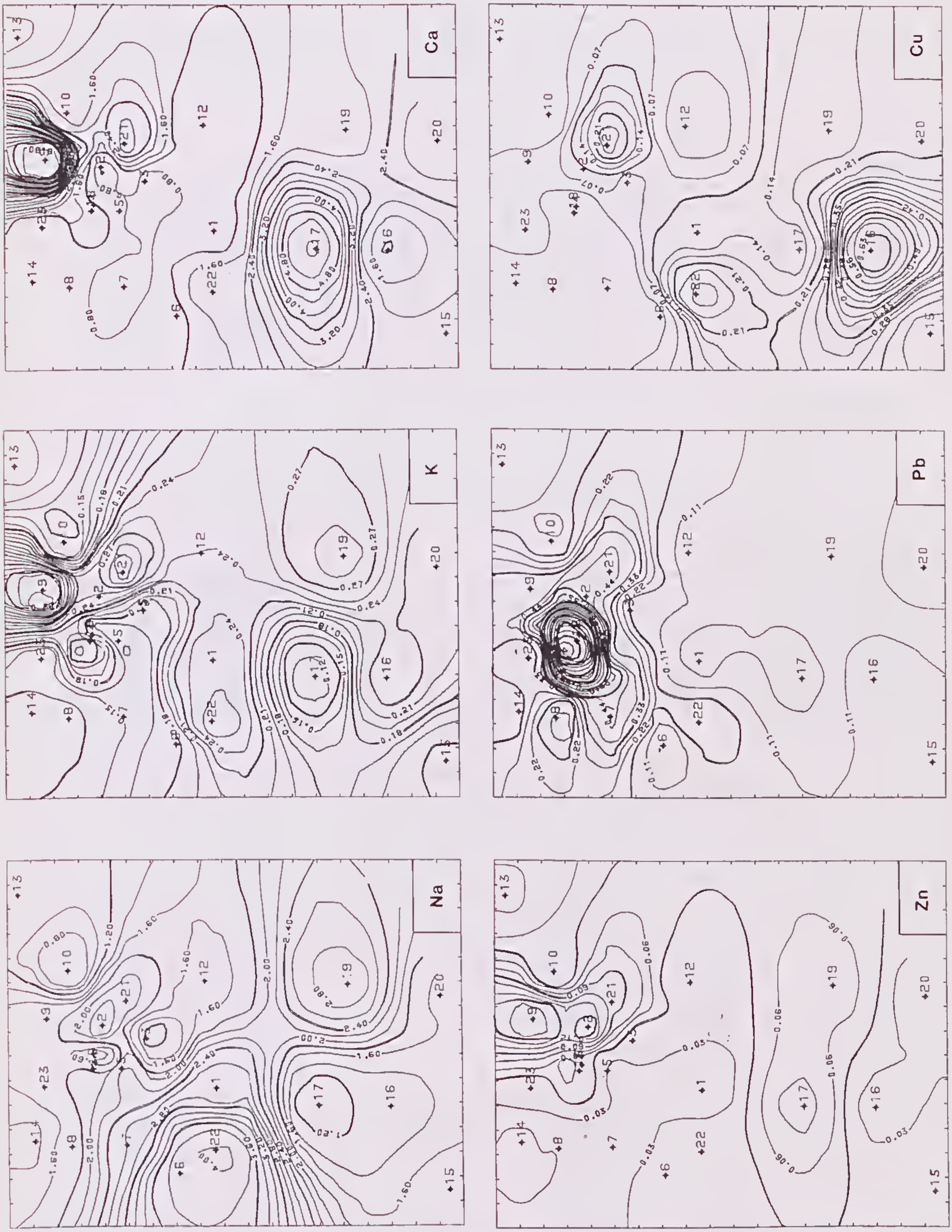


Figure 3.—Contours of trace element distribution in Perth. It must be born in mind that the results for each site were obtained on different days, and therefore under different meteorogical conditions (see text). The boundaries for each plot correspond to those of Figure 1.

Table 1

The results of atomic absorption spectrophotometric analysis of six elements from 23 sites are given in micrograms per cubic metre of air sampled. The fine particle mass concentration in micrograms per cubic metre, obtained by the nephelometer, is also given (see also text).

Code	Site	Na $\mu g/m^3$	K $\mu g/m^3$	Ca $\mu g/m^3$	Cu $\mu g/m^3$	Pb $\mu g/m^3$	Zn $\mu g/m^3$	FPMC $\mu g/m^3$ (24 hour avergage)
01	A Murdoch	2.69 ± 0.07	0.25 ± 0.01	0.97 ± 0.07	0.12 ± 0.01	0.04 ± 0.01	0.02 ± 0.01	15
02	B Rivervale	2.41 ± 0.06	0.25 ± 0.01	3.26 ± 0.11	0.09 ± 0.01	0.47 ± 0.01	0.16 ± 0.01	129
03	C Bentley	1.01 ± 0.03	0.17 ± 0.01	0.63 ± 0.02	0.06 ± 0.01	0.09 ± 0.01	0.03 ± 0.01	144
04	D CBD 57 Murray	0.46 ± 0.01	0.08 ± 0.01	0.66 ± 0.02	0.01 ± 0.01	0.85 ± 0.01	0.04 ± 0.01	—
05	E S Perth	2.44 ± 0.06	0.14 ± 0.01	0.71 ± 0.02	0.00 ± 0.01	0.24 ± 0.01	0.02 ± 0.01	91
06	F N Fremantle	3.92 ± 0.10	0.17 ± 0.01	1.05 ± 0.03	0.00 ± 0.01	0.05 ± 0.01	0.04 ± 0.01	148
07	G Claremont	2.62 ± 0.07	0.15 ± 0.01	0.64 ± 0.02	0.00 ± 0.01	0.46 ± 0.01	0.02 ± 0.01	118
08	H Floreat	1.76 ± 0.05	0.13 ± 0.01	0.88 ± 0.02	0.00 ± 0.01	0.04 ± 0.01	0.02 ± 0.01	114
09	I Bayswater	1.78 ± 0.05	0.41 ± 0.01	9.89 ± 0.29	0.04 ± 0.01	0.35 ± 0.01	0.16 ± 0.01	182
10	J Redcliffe	0.54 ± 0.01	0.12 ± 0.01	1.10 ± 0.03	0.00 ± 0.01	0.09 ± 0.01	0.03 ± 0.01	61
11	K Chidlow	3.02 ± 0.08	0.20 ± 0.01	0.77 ± 0.02	0.01 ± 0.01	0.06 ± 0.01	0.04 ± 0.01	167
12	L Thornlie	1.56 ± 0.04	0.24 ± 0.01	0.85 ± 0.02	0.00 ± 0.01	0.08 ± 0.01	0.04 ± 0.01	129
13	M Swanview	1.14 ± 0.03	0.10 ± 0.01	0.34 ± 0.01	0.00 ± 0.01	0.06 ± 0.01	0.01 ± 0.01	110
14	N Doubleview	1.29 ± 0.04	0.13 ± 0.01	0.89 ± 0.03	0.01 ± 0.01	0.38 ± 0.01	0.04 ± 0.01	—
15	O Rockingham	1.68 ± 0.04	0.13 ± 0.01	2.03 ± 0.09	0.15 ± 0.01	0.12 ± 0.01	0.04 ± 0.01	99
16	P Orelia	1.30 ± 0.04	0.24 ± 0.01	1.14 ± 0.07	0.67 ± 0.02	0.14 ± 0.01	0.02 ± 0.01	84
17	Q Bangenup	1.07 ± 0.03	0.11 ± 0.01	5.71 ± 0.19	0.12 ± 0.01	0.04 ± 0.01	0.08 ± 0.01	91
18	R CBD W Queens Bdg	2.71 ± 0.07	0.34 ± 0.01	2.16 ± 0.11	0.02 ± 0.01	1.94 ± 0.05	0.08 ± 0.01	218
19	S Armadale Dump	2.92 ± 0.08	0.29 ± 0.01	1.81 ± 0.10	0.16 ± 0.01	0.07 ± 0.01	0.07 ± 0.01	247
20	T Mundijong	1.55 ± 0.04	0.21 ± 0.01	3.07 ± 0.12	0.20 ± 0.01	0.04 ± 0.01	0.02 ± 0.01	224
21	U Kewdale	2.13 ± 0.06	0.31 ± 0.01	3.20 ± 0.13	0.27 ± 0.01	0.48 ± 0.01	0.10 ± 0.01	1890
22	V Beaconsfield	4.09 ± 0.10	0.27 ± 0.01	2.01 ± 0.09	0.32 ± 0.01	0.22 ± 0.01	0.04 ± 0.01	243
23	W Joondanna	1.64 ± 0.04	0.14 ± 0.01	0.71 ± 0.06	0.06 ± 0.01	0.25 ± 0.01	0.04 ± 0.01	194

Judged by the source results, the zinc peak to the east of the city could result from the hospital incinerator burning. Bush fires and cement works can be seen as sources of potassium, and the weak peaks down the east centre of the map (Figure 3 - K) may result from a combination of both these sources in addition to K from seaspray. No source for copper was found (see Table 4), but the small peaks at Orelia, Kewdale and South Fremantle appear to be associated with industrial areas.

Both bush fires and cement works are seen to be sources for calcium in the air (Table 4) and cannot be separated. However, cement works are considered to be a relatively continuous source, whereas bush fires are highly erratic. The peak at Banganup (site 17 in Figure 1) appears to be caused by proximity to the Cockburn cement works.

There were a number of outbreaks of bush fires, due to high temperatures in February (see Table 2), which at times increased the number of particles in the air over

Table 2

Measured SO_2 and NO_x concentration for a 24 hour sampling period at each site (in micrograms per cubic metre).

Daily average temperature on the days of sampling; obtained from the meteorology station at the airport.

Site code	Date	Locality	SO_2 $\mu g\ m^{-3}$	NO_x $\mu g\ m^{-3}$	Temp. °C
1	10.1.85	Murdoch	1.2	19	23
2	14.1.85	Rivervale	N.D.	12	20
3	16.1.85	Bentley	0.8	10	25
4	17.1.85	C.B.D.E. 57 Murray Street	1.7	32	25
5	22.1.85	South Perth Zoo	1.6	45	21
6	23.1.85	North Fremantle	4.1	37	26
7	24.1.85	Claremont	1.0	62	22
8	29.1.85	City Beach Bold Park	1.1	16	19
9	30.1.85	Bayswater	1.1	51	24
10	31.1.85	Redcliffe	N.D.	20	29
11	2.2.85	Chidlow (off map)	N.D.	15	22
12	5.2.85	Thornlie	1.9	32	28
13	6.2.85	Swanview	N.D.	10	29
14	8.2.85	Doubleview	3.5	15	28
15	12.2.85	Rockingham	1.3	15	29
16	13.2.85	Orelia	2.4	6	34
17	14.2.85	Bangenup	3.5	7	28
18	19.2.85	C.B.D.W. Queen's Bdg	14.3	94	32
19	20.2.85	Armadale Tip	1.3	14	33
20	23.2.85	Mundijong	1.4	27	29
21	26.2.85	Kewdale	8.4	11	31
22	5.3.85	Beaconsfield	1.0	13	29
23	7.3.85	Joondanna	1.3	26	21

N.D. not detectable

Table 3

Atomic absorption spectrophotometric analyses of sources are given for six elements in micrograms per cubic metre. The samples were obtained placing fixed flow samplers in the vicinity of the source (see text). Where all the elements are high, as they are for the cement works, it is likely that a more concentrated sample of the source was taken.

Sample	Site	Na $\mu g/m^3$	K $\mu g/m^3$	Ca $\mu g/m^3$	Cu $\mu g/m^3$	Pb $\mu g/m^3$	Zn $\mu g/m^3$
	PETROL						
5.8	A	4.12±0.33	1.18±0.14	5.29±0.24	0.27±0.07	449±12	0.82±0.08
5.9	B	2.35±0.17	0.59±0.07	3.38±0.13	0.00±0.01	460±12	0.74±0.05
5.10	C	3.14±0.23	1.57±0.11	4.12±0.17	0.00±0.01	474±12	0.71±0.05
5.11	D	7.06±0.64	3.53±0.31	9.41±0.45	0.00±0.01	421±13	3.06±0.18
	DIESEL						
5.5	B	11.8±0.66	11.8±0.4	13.4±0.49	0.69±0.11	1.77±0.24	4.31±0.19
6.5	C	4.90±0.51	1.96±0.2	—	0.00±0.01	1.28±0.23	30.4±0.74
7.5	D	7.84±0.57	9.80±0.40	—	0.88±0.12	4.80±0.30	4.31±0.19
3.5	1E	2.35±0.56	1.18±0.2	4.35±0.59	0.00±0.01	2.35±0.29	0.59±0.13
3.6	2E	7.84±0.73	13.1±0.54	3.27±0.62	1.05±0.16	2.61±0.32	0.65±0.15
3.7	3E	4.71±0.59	2.35±0.29	2.94±0.56	0.00±0.01	0.59±0.25	0.82±0.14
3.8	4E	7.06±0.66	9.41±0.44	5.88±0.62	1.88±0.16	2.35±0.29	0.82±0.14
6.8	DE	9.41±0.69	4.7±0.3	8.94±0.43	0.59±0.13	0.00±0.01	2.47±0.17
	COAL FIRED						
6.3	A	2.16±0.13	1.96±0.08	1.57±0.07	0.06±0.02	0.00±0.01	0.77±0.04
6.4	B	4.31±0.25	1.96±0.12	3.80±0.16	0.01±0.01	0.00±0.01	1.14±0.06
6.5	C	6.27±0.30	3.14±0.15	23.8±0.58	0.31±0.05	0.51±0.09	7.84±0.21
6.6	D	3.14±0.23	1.57±0.11	5.33±0.19	0.29±0.04	0.00±0.01	2.90±0.10
6.7	E	1.76±0.12	2.55±0.09	1.88±0.08	0.10±0.02	0.00±0.01	1.02±0.04
	BUSH FIRES						
5.1	A	61.2±1.8	142±3.2	152±3.5	2.18±0.17	2.12±0.29	5.29±0.23
5.2	B	17.6±0.9	17.6±0.6	22.9±0.7	1.06±0.14	1.52±0.28	2.12±0.16
5.3	C	67.1±1.9	222±4.9	32.4±0.9	0.00±0.01	0.59±0.26	2.25±0.17
6.1	D	70.2±1.6	108±2.4	248±6.5	0.31±0.01	0.00±0.01	3.57±0.12
6.2	E	49.0±1.2	79.2±1.7	141±3.9	0.29±0.04	0.00±0.01	0.67±0.05
	CEMENT WORKS						
4.1	CE1	400±9.1	4400±110	1590±78	1.91±0.20	9.56±0.50	10.6±0.53
4.2	CE2	435±9.8	4720±120	2300±95	2.35±0.20	12.1±0.56	13.5±0.59
4.3	CE3	290±6.5	3190±80	1190±55	1.57±0.13	8.43±0.38	9.02±0.39
4.4	CE4	586±16.6	5820±140	1870±72	1.77±0.14	11.2±0.44	7.65±0.36
4.5	CE5	460±10.3	5000±126	1930±86	0.44±0.16	11.5±0.54	7.06±0.05
4.6	CE6	596±13.4	5900±149	3870±140	4.31±0.29	18.4±0.79	47.8±1.41
	BRICKWORKS						
9.1	MB1	1.02±0.04	0.88±0.03	2.82±0.08	0.08±0.01	0.22±0.01	0.49±0.02
9.2	MB2	2.02±0.06	1.03±0.03	1.89±0.10	0.06±0.01	0.34±0.01	1.03±0.03
9.3	MB3	0.27±0.03	0.59±0.02	0.90±0.04	0.00±0.01	0.09±0.01	0.43±0.01
9.4	MB4	0.00±0.00	0.27±0.01	0.40±0.03	0.01±0.01	0.07±0.01	0.31±0.01

Table 4

Sources diagnostic elements shows the mean and standard deviation (S.D.) of each group of samples taken from the six sources listed in Table 3. Also shown are earlier results from household and hospital incinerators in which insufficient samples were obtained to yield a standard deviation.

Source	Na $\mu g/m^3$	Na S.D.	K $\mu g/m^3$	K S.D.	Ca $\mu g/m^3$	Ca S.D.	Cu $\mu g/m^3$	Cu S.D.	Pb $\mu g/m^3$	Pb S.D.	Zn $\mu g/m^3$	Zn S.D.
PETROL 4 Samples	4.17	2.06	1.72	1.27	5.55	2.69	0.07	0.13	**450.6**	22.4	1.33	1.15
DIESEL 8 Samples	6.98	2.96	6.78	4.77	6.47*	4.05	0.64	0.65	1.97	1.47	5.54	10.2
COAL FIRED 5 Samples	3.53	1.82	2.24	0.61	7.28	9.38	0.13	0.12	0.10	0.23	2.73	2.98
BUSH FIRES 5 Samples	53.02	21.37	*114.0*	75.9	*119.0*	93.5	0.75	0.89	0.85	0.95	2.78	1.74
CEMENT WORKS 6 Samples	461	116	**4840**	1000	**2110**	908	2.06	1.28	11.9	3.49	16.0	15.9
BRICK WORKS 4 Samples	0.83	0.90	0.69	0.34	1.50	1.07	0.03	0.04	0.18	0.13	0.56	0.32
HOUSEHOLD INCINERATOR 2 Samples	26.7	—	21.6	—	21.6	—	0.54	—	5.40	—	8.08	—
HOSPITAL INCINERATOR 2 Samples	5590	—	3610	—	900	—	123	—	1000	—	*6500*	—

*6 samples

Table 5

Atomic absorption spectrophotometric analyses of six elements are given for the six sites that were sampled twice. Series 1 was sampled before Chrismas in 1984 and Series 2 during January and February 1985. The vertical arrows indicate an increase of pollution from series 1 to series 2. Excellent within-site agreement is shown in bold and a good agreement by italics. Strong reverse trends, such as calcium for Armadale (site was near dumping area), are thought to have been caused by some special, but unknown circumstance.

Site		Na $\mu g/m^3$	Na error	K $\mu g/m^3$	K error	Ca $\mu g/m^3$	Ca error	Cu $\mu g/m^3$	Cu error	Pb $\mu g/m^3$	Pb error	Zn $\mu g/m^3$	Zn error
RAAF CLAREMONT	1	0.91	±0.03	0.041	±0.002	*0.45*	±0.01	0.097	±0.002	0.157	±0.004	**0.017**	±0.001
	2	2.62	±0.07	0.150	±0.004	*0.64*	±0.02	0.002	±0.001	0.463	±0.013	**0.018**	±0.001
WAIT Bentley	1	*1.36*	±0.04	0.041	±0.002	0.19	±0.01	0.004	±0.001	*0.071*	±0.001	0.005	±0.001
	1	2.16	±0.06	0.123	±0.003	0.26	±0.01	0.004	±0.001	*0.093*	±0.002	0.007	±0.001
	2	*1.02*	±0.03	0.173	±0.004	0.63	±0.02	0.062	±0.002	*0.086*	±0.002	0.031	±0.001
Rockingham	1	2.69	±0.07	0.233	±0.006	0.70	±0.02	0.050	±0.002	0.059	±0.002	0.011	±0.001
	2	1.68	±0.04	0.132	±0.003	2.03	±0.09	0.148	±0.003	0.116	±0.003	0.041	±0.001
Orelia	1	3.16	±0.08	*0.286*	±0.007	*0.96*	±0.02	0.207	±0.005	0.052	±0.002	**0.027**	±0.001
	2	1.30	±0.04	*0.242*	±0.006	*1.14*	±0.07	0.668	±0.018	0.138	±0.003	**0.023**	±0.001
Armadale Dump	1	0.81	±0.02	**0.292**	±0.007	3.18	±0.09	*0.186*	±0.004	**0.067**	±0.002	0.021	±0.001
	2	2.92	±0.08	**0.291**	±0.007	1.81	±0.10	*0.156*	±0.003	**0.067**	±0.002	0.067	±0.002
Queen's Bldg	1	0.84	±0.02	0.056	±0.001	0.34	±0.01	0.045	±0.001	0.488	±0.013	**0.016**	±0.001
	2	2.71	±0.07	0.337	±0.008	2.16	±0.11	0.016	±0.001	1.938	±0.045	**0.016**	±0.001

the city. A serious bush fire on February 26 had a marked effect on parts of the city, and was a contributary cause to the very high particle count obtained at Kewdale (site 21) at that time (see Table 1). For this reason this site caused a high peak in the graphic display of Figure 2-FPMC. Not included in the plottings is the site in Chidlow (site 11) because it is off the map in Figure 1; this site was rather considered to be a control spot in an almost rural "clean air" area outside the city. Some of the FPMC values are doubtful due to instrumentation problems.

Some of the trace elements show a sympathetic relationship. Thus Zn and K are significantly correlated ($r=0.65$, $p<0.01$); both are known to be derived from the emissions of incinerators. As mentioned above car traffic and its pollutants (Pb, NO_x) shows the highest concentrations in the CBD, and as a result Pb and NO_x correlate with a coefficient of 0.73 ($p<0.01$).

In comparison with a previous sampling (December 1984) some of the trace element concentrations increased—see Table 5.

Conclusions

The trace element results link lead to petrol engines, calcium to cement works, potassium to bush fires and cement works, and zinc to hospital incinerators. The contour maps of these elements for Perth show that none

Table 6

Daily average windspeed, maximum wind speed, gusts and predominant wind direction on the days of sampling. The data were obtained at the meterological station at the Perth airport.

Site	Date	Mean Speed in knots	Max Speed in knots	Gusts	Direction range
Murdoch	10.1.85	6	20	No	SW Steady
Rivervale	14.1.85	7	28	Yes	SE→SW→SE
Bentley	16.1.85	15	41	Yes	E Steady
CBD E	17.1.85	11	36	Yes	SE→S
S Perth (Zoo)	22.1.85	7	26	Yes	Mainly SW
N Fremantle	23.1.85	5	20	Inter	Mainly SW
Claremont	24.1.85	6	25	Yes	SW Steady
Floreat	29.1.85	6	26	Yes	SW→S
Bayswater	30.1.85	8	28	Yes	SE→SW→SE
Redcliffe (Airport)	31.1.85	7	25	Inter	Mainly NE
Chidlow (Off Map)	2.2.85	8	25	Inter	SW Steady
Thornlie	5.2.85	10	35	Yes	SE
Swanview	6.2.85	11	29	Yes	E Steady
Doubleview	8.2.85	4	22	Inter	S Variable
Rockingham	12.2.85	8	27	Yes	E→SW→E
Orelia	13.2.85	5	25	Inter	E Variable
Bangenup	14.2.85	10	31	Yes	Mainly S
CBD W	19.2.85	4	20	No	SW Var→E
Armadale Tip	20.2.85	8	16	No	Mainly SW Var
Mundijong	23.2.85	4	20	No	E→W→S→E→SE
Kewdale	26.2.85	5	21	Inter	N→W→S→E Var
Beaconsfield	5.3.85	4	20	Inter	SW Variable
Joondanna	7.3.85	6	23	Yes	SE→W→S

The mean and maximum velocities were taken from approximately 0830 on the stated date until about 0830 on the following day. Gusts inter-intermediate, some gusts experienced during the course of the day.

of these sources of air pollution are out of control at the present time, although all should be considered in any plans to keep Perth air clean. Sulphur dioxide and nitrogen oxides levels are low in the suburbs, but less so in the CBD and near industrial areas.

The SO_2-values are, compared with overseas cities, very low. A WHO study group (World Health Organization 1979) establishing limits for SO_2 concentrations recommended yearly arithmetic means are kept below 40 - 60 $\mu g\ m^{-3}$ SO_2 to prevent health problems due to long term exposure; Perth's SO_2 levels fortunately are not even near this limit (Table 2).

Some of the nephelometer readings were erratic, therefore a comparison of the FPMC with other cities would be unreliable.

Although the area coverage for this study was satisfactory, it would be desirable for future surveys to monitor the air pollution at all sites simultaniously in order to reduce meteorlolgical influences.

Perth is not a city as yet plagued with air pollution problems. It is still a far cry from Tokyo, Los Angeles or Sydney (Milne *et al.* 1983, Roberts *et al.* 1983) in the contamination of the air its inhabitants have to breathe. Located in an area with a comparable climate to Los Angeles with high sun intensities, the trapping of poisonous products and the production of photochemical smog could become a serious problem. Increasing traffic density, more heavy industry, greater incineration of waste, and salt from the sea, all tend to promote photochemical smog for the future.

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